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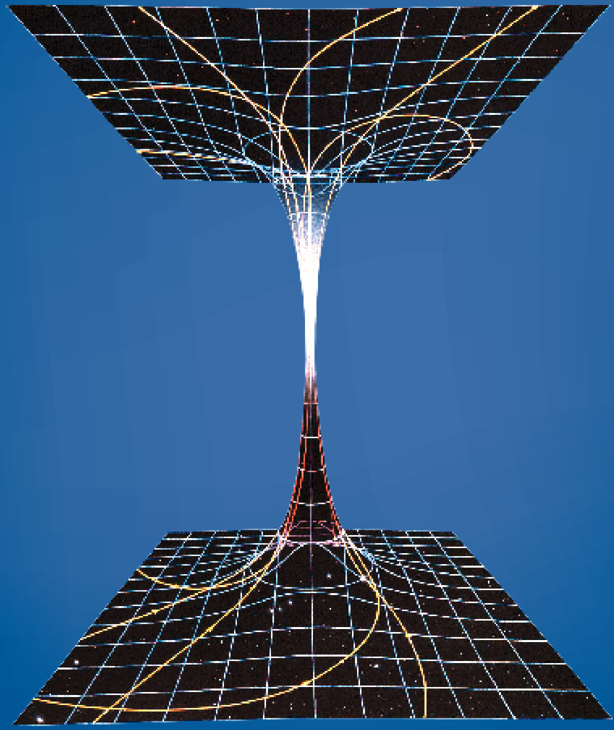
Impossible: Physics beyond the Edge

Course Guidebook

Professor Benjamin Schumacher
Kenyon College



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Professor Schumacher has spent sabbaticals working at Los Alamos National Laboratory and at the Institute for Quantum Information at the California Institute of Technology, where he was a Moore Distinguished Scholar. He has also done research at the Isaac Newton Institute of the University of Cambridge, the Santa Fe Institute, the Perimeter Institute, the University of New Mexico, the University of Montreal, the University of Innsbruck, and the University of Queensland.

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Impossible: Physics beyond the Edge

Scope:

> "The only way of discovering the limits of the possible
> is to venture a little way past them into the impossible."
> Clarke's second law, Arthur C. Clarke, 1960.

Science tries to study the world as it is, not the world as it might be. So it comes as a bit of a surprise that scientists—and physicists in particular—often spend their time thinking about impossible things. Understanding exactly what is impossible, and why, is one of the best ways to explore the meaning of the fundamental laws of nature.

The word "impossible" can be used to describe many different things, from logical self-contradictions to events that are merely extremely improbable. Some inventions and discoveries were once called "impossible"—often only a short time before they were achieved. The wise prophet is cautious about claiming that something can never be done.

Yet some ideas, like perpetual motion machines, really do appear to be impossible. Over the past 2 centuries, physicists have developed the laws of thermodynamics to describe energy and its transformations. The first law tells us that energy cannot be created out of nothing. The second law limits our ability to transform heat energy into useful work and establishes a direction for the flow of time. The third law puts absolute zero, the ultimate limit of cold, forever beyond our reach. These laws, tested in innumerable ways, have resolved problems as gigantic as the energy source of the Sun and as diabolical as Maxwell's mischievous demon.

Other branches of physics provide their own insights into the meaning of the impossible. Chaos theory tells us that, even if a system's future is mathematically predetermined, it may nevertheless be impossible in practice to predict it. Our knowledge of the future is forever limited.

Two of the most popular devices of science fiction stories are the time machine and the faster-than-light spaceship. Both of these means of transport would lead to seemingly unresolvable paradoxes and thus are regarded as impossible. In fact, their impossibility is closely related. To explain this link, we delve into Einstein's special theory of relativity. Our particular focus is on the structure of space-time, the 4-dimensional world

that encompasses all points in space at all moments in time. The events, world lines, and light cones of space-time describe the possible relations of cause and effect in our universe. Central to this discussion is the concept of information and how it may be transmitted from one place to another. Not only can we not travel into the past or faster than light, we cannot even send signals there.

Einstein's general theory of relativity describes gravity as the curvature of space-time. We can therefore use our understanding of space-time to analyze the gravitational field of a black hole and show the impossibility of escaping from within its event horizon. We can also discuss more speculative ideas like wormholes and exotic matter that may yet overturn our long-held beliefs about cause and effect.

No discussion of the laws of physics would be complete without an account of symmetry. A symmetry is a transformation that leaves a system or a geometrical figure unchanged. We are most familiar with simple reflection symmetry, but physics makes use of symmetries of all types. The laws of physics are highly symmetric, and each symmetry is connected to a conservation law. Yet there remain some curious asymmetries in nature. By observing the decays of unstable nuclei and elementary particles, it is possible to find tiny differences between left and right or between matter and antimatter. The world in the mirror is almost, but not quite, like our own.

Not all geometrical transformations—like the similarity of large and small shapes—are symmetries of nature. The square-cube law shows that an object or a living creature is not equivalent to a magnified or miniature version of the same. (Thus another science fiction standby, the menace of the giant insects, is seen to be impossible.)

No revolution in physics shifted the boundary of the impossible more than the discovery of quantum mechanics. Quantum uncertainty means that even empty space contains energy. Particles may tunnel into places forbidden to them by Newton's laws. Yet the rules of the quantum world are not just "anything goes." Conservation laws determine what particle reactions can occur. And quantum mechanics introduces a new principle of information: Quantum information cannot be perfectly cloned. Without this unfamiliar yet central principle of nature, quantum entanglement would provide the means to transmit messages into the past.

Our exploration of the impossible leads us to ask profound questions about the laws of physics. How do they work? What is their basis? We describe how the laws of electromagnetism enforce the conservation of electric charge—a geometric insight that also applies to gravitation and the conservation of energy. We discuss some of the central characteristics of physical law: symmetry, information, and probability. Although it is impossible to predict the future development of physics, we can nevertheless use the insights we have gained to speculate where the true boundary between possible and impossible must lie.

Lecture One
From Principles to Paradoxes and Back Again

Scope:

What do we mean by "the impossible"? Why should science—which studies the facts about nature—take an interest in things that could never exist? In this lecture, we address these and other questions and define some significant terms.

Outline

I. Why is it useful to study the impossible?

- **A.** The distinction between the possible and the impossible is a very important aspect of the laws of physics.
- **B.** Thinking about the impossible is an important tool for appreciating the meaning of physical law. Whenever we find that something is really impossible, there is a great principle of physics at work.
- **C.** New discoveries may change our knowledge of the laws of physics. What is considered impossible today may turn out to be possible after all.
- **D.** Thinking seriously about the impossible is a game that stimulates our imagination and sharpens our understanding.

II. What do we mean when we say that "x is impossible"?

- **A.** If x is an absolute impossibility, it involves a logical or mathematical contradiction. Its impossibility does not rely on any special assumptions, though we must define our terms very carefully.
- **B.** If x is a derived impossibility, it goes against some accepted assumption about the world.
- **C.** We will mostly concern ourselves with physical impossibilities, which contradict the known laws of physics.
- **D.** If x is a statistical impossibility, then x may be possible in principle but is so unlikely that we may regard it as effectively impossible.

III. Great thinkers in the history of science have made use of the impossible and helped us to understand its meaning.

- **A.** Greek mathematician Euclid used the impossible to help prove propositions of geometry. His method is called proof by contradiction, or reductio ad absurdum.
- **B.** English physicist Isaac Newton discovered general laws of motion and gravitation, which he set forth in his greatest work, the *Mathematical Principles of Natural Philosophy*. He uses arguments based on physical impossibilities to show how the laws fit together.
- **C.** Scottish physicist James Clerk Maxwell revolutionized our ideas of heat and motion by arguing that the laws of thermodynamics are statistical laws, rather than exact rules.

IV. What are the goals of this course?

- **A.** To demonstrate how the laws of physics tell us that certain things are impossible—and in each case, what type of impossibility is involved.
- **B.** To show how different impossible things (e.g., time travel and faster-than-light communication) are related to each other.
- **C.** To use the study of the impossible to obtain insights about the laws of nature and to identify deep principles of space and time, cause and effect, energy and information.

Questions to Consider:

1. Think of an impossibility not mentioned in the lecture and classify it as an absolute, derived, or statistical impossibility.
2. Euclid, Isaac Newton, and James Clerk Maxwell each imagined something impossible—a triangle, a dumbbell, or a container of gas—and used it to draw a conclusion. Discuss the differences between the 3 arguments.
3. The idea of the impossible is useful in mathematics and the physical sciences. Can you think of impossibilities in the social sciences, like economics? What type of impossibilities are they?

Lecture Two
Almost Impossible

Scope:

Many technological developments were believed to be impossible before they were achieved. Heavier-than-air flight, radio communication across the ocean, and space travel were all once regarded as "utter bilge." These examples warn us against failures of imagination, and they teach us to be careful as we try to draw the line between the possible and the impossible.

Outline

I. Science fiction writer Arthur C. Clarke proposed 3 laws about speculating on the future.

- **A.** First law: "When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong."
- **B.** Second law: "The only way of discovering the limits of the possible is to venture a little way past them into the impossible."
- **C.** Third law: "Any sufficiently advanced technology is indistinguishable from magic."

II. History provides many examples of technological advances once believed to be impossible.

- **A.** In 1903, astronomer Simon Newcomb concluded that powered heavier-than-air flight was impossible without new advances in science. Within 2 months, Orville and Wilbur Wright flew their first airplane.
- **B.** In 1956, Richard van der Riet Woolley, the British Astronomer Royal, proclaimed space travel "utter bilge." Sputnik was launched the following year, and human spaceflight began soon thereafter.
- **C.** Other technologies once thought impossible include radio, television, nuclear energy, and widespread computing.
- **D.** Even science fiction writers have not reliably foreseen technological progress.

III. History also provides examples of scientific discoveries that contradicted accepted ideas of the possible.

- **A.** In 1835, philosopher Auguste Comte proclaimed that we could never discover the chemical compositions of stars. By 1860, a new technique—spectroscopy—had revealed their makeup.
- **B.** Before 1970, it was believed that no living things could grow and reproduce at temperatures much above 70°C. Since then, bacteria have been found that live at much higher temperatures (up to 112°C in deep-ocean volcanic vents).

IV. What is the main hazard in stating that something is impossible? A failure of imagination!

- **A.** No mere technical difficulty makes something impossible. If it does not contradict the laws of physics, then it is possible (even if we do not know how to do it).
- **B.** We should always keep in mind what sort of impossibility we mean: absolute, derived or statistical.
- **C.** Despite our best efforts, we may get some things wrong. Some of our claims may someday seem as foolish as those of Newcomb and Woolley.

Questions to Consider:

1. Technological advances often turn the impossible into a reality. Suppose a scientist or engineer a century ago were somehow able to see the modern world. Which new technologies would be most surprising? Which ones would be least surprising? Why?
2. We discussed several things that were once thought to be impossible but turned out to be possible. Can you think of an example of the reverse—a scientific or technological idea that was once thought possible but has proved to be impossible?

Lecture Three
Perpetual Motion

Scope:

For centuries, would-be inventors have proposed machines designed to move endlessly without application of outside force. These machines never work because they produce more energy than they consume. Quantum physics teaches us that "empty space" actually contains vast amounts of energy, which has motivated more recent efforts to obtain energy from nothing. Yet these modern attempts at perpetual motion machines are also doomed to fail—probably!

Outline

I. A perpetual motion machine is a device that can do work forever without any external input. Although designs for these go back almost 1000 years, these devices are impossible.

- **A.** Work is defined as a force acting through a distance. Work is done when accelerating an object, overcoming friction, or lifting a weight against gravity.
- **B.** The classic design for a perpetual motion machine is the unbalanced wheel, but actual models do not work.
- **C.** Flemish physicist Simon Stevin discovered the relevant fundamental principle of mechanics: A machine that does not change in some way cannot produce work.

II. In the 18^{th} and 19^{th} centuries, physicists introduced the idea of energy, originally called vis viva.

- **A.** Kinetic energy is energy an object possesses due to its motion through space. Faster speeds mean greater kinetic energy.
- **B.** Potential energy is energy an object possesses due to its position in space. An object that is placed higher in a gravitational field will have a higher potential energy.
- **C.** During the flight of a thrown ball with only gravity acting on it, the total mechanical energy (kinetic plus potential) remains constant.

III. Heat is a form of energy.

A. Heat was once believed to be an intangible fluid called caloric. Hotter objects contained more caloric than colder ones.

B. Benjamin Thompson, Count Von Rumford, discovered that heat was created by work when he observed the boring of a brass cannon.

C. Julius Mayer and James Joule showed that heat is a form of energy, calculating how much heat corresponds to how much work. The basic unit of energy is called a joule.

D. Forms of energy other than heat include chemical energy, electrical energy, radiant energy, and so forth.

IV. Total energy, including all forms, is always conserved.

A. Energy may change in form and move from place to place, but it can never be created or destroyed.

B. Conservation of energy is a fundamental law of nature that we call the first law of thermodynamics.

C. Energy conservation is the underlying reason that perpetual motion machines are impossible. No machine can produce energy from nothing.

D. According to quantum mechanics, even supposedly empty space contains energy, called vacuum energy or zero-point energy, that produces small forces and can be used to perform work via the Casimir Effect.

E. Conservation of energy still holds, however, so that vacuum energy cannot be used to create a perpetual motion machine.

Questions to Consider:

1. The Earth has moved in its orbit around the Sun for several billion years without running down. Explain why this does not count as a perpetual motion machine.

2. Explain why the concept of heat energy is an improvement over the caloric theory of heat.

3. An inventor shows you the blueprints for a perpetual motion machine, all full of wheels and gears and pulleys and so forth. Your job is to find the flaw in the design. What things would you look for?

Lecture Four
On Sunshine and Invisible Particles

Scope:

The Sun is powered by nuclear reactions, with mass converting to energy according to Einstein's famous formula: $E = mc^2$. But beta decay seems to violate this formula, with some of the reaction's energy vanishing without a trace. Wolfgang Pauli and Enrico Fermi proposed that an almost invisible particle, the neutrino, carries the energy away. We can now detect neutrinos from the Sun, giving us a way to study the reactions in its core—a study that posed a puzzle of its own, only recently resolved.

Outline

I. The law of energy conservation has endured many challenges. The first of these was the energy of sunlight.

- **A.** The Sun is very hot and bright and has emitted radiant energy for a very long time. What is the source of this energy?
- **B.** Chemical energy is insufficient. Even if the whole Sun were made of fuel and oxygen, it could only burn for a few thousand years.
- **C.** Hermann von Helmholtz suggested that the Sun is slowly contracting, its potential energy becoming heat. But again, given the mass and size of the Sun, it would only have energy for a limited time.
- **D.** Nuclear energy provides the explanation. The energy released in nuclear reactions is associated with a small decrease in mass ($E = mc^2$). A small amount of mass corresponds to a very large amount of energy.
- **E.** The energy source of the Sun is nuclear fusion, in which 4 hydrogen nuclei combine to form 1 helium nucleus, releasing enough energy to power the Sun for billions of years.

II. Nuclear physics poses its own challenge to the law of energy conservation: beta decay, where a nucleus transforms itself and emits an electron.

- **A.** Energy conservation seems to predict that the electron has a fixed energy, but in actual experiments, the electrons can have a whole range of energies.
- **B.** Niels Bohr suggested that energy conservation is only approximate. Large-scale energy conservation would only be a statistical law.
- **C.** Wolfgang Pauli and Enrico Fermi proposed that an unseen particle is produced in beta decay: the neutrino.
- **D.** The neutrino moves at or near the speed of light. It carries energy but can pass through ordinary matter without interacting and is almost invisible.
- **E.** Neutrinos were finally observed directly in 1956.

III. Neutrinos provide us a window on the nuclear reactions inside the Sun. But this leads to another puzzle.

- **A.** An ultrasensitive experiment in the Homestake Gold Mine measured the number of neutrinos coming from the Sun, and only a third of the expected number was observed.
- **B.** The Homestake experiment was finally explained by the theory of neutrino oscillations.
    - **1.** Neutrinos come in 3 types—electron, muon, and tau—and can oscillate from one type to another.
    - **2.** The Sun produces electron neutrinos. By the time they reach Earth, the 3 types are present in about equal numbers. Since the Homestake experiment only looked for one type, it only saw a third of the neutrinos.
    - **3.** In 2001, the Sudbury Neutrino Observatory detected solar neutrinos of all 3 types, confirming the theory of neutrino oscillations.

Questions to Consider:

1. Hermann von Helmholtz argued that, without an internal source of heat, the Earth must be slowly cooling off. By calculating backward in time, he reasoned that Earth must have been molten only a few tens of millions of years ago. Since the geological evidence indicates otherwise, Earth must have a continual source of internal heat. Can you guess what it is? (The answer will be discussed in Lecture 16. No fair peeking.)

2. Imagine that you are a physicist in 1930. Which would you find more likely, the "energy is not quite conserved in beta decay" theory of Niels Bohr, or the "invisible neutrino" theory of Wolfgang Pauli and Enrico Fermi? Which idea would have seemed more persuasive at the time? Explain your answer.

Lecture Five
Reflections on the Motive Power of Fire

Scope:

The world contains immense amounts of heat energy. Why can we not turn it into useful work? Two hundred years ago, the French engineer Sadi Carnot realized that only a temperature difference can be used to generate work from heat, and some waste heat must always be lost. This discovery led to the formulation of the second law of thermodynamics, which is best understood in terms of entropy.

Outline

I. A perpetual motion machine of the second kind extracts heat from an object and turns it into work. Such machines do not violate the conservation of energy but are nevertheless impossible.

II. Sadi Carnot analyzed steam engines in *Reflections on the Motive Power of Fire*. His work led to the development of thermodynamics.

- **A.** Carnot's brilliant insight was that a heat engine requires a temperature difference to operate. No work can be done unless heat flows from hot to cold.
- **B.** The engine absorbs heat from a hot body, extracts some of it as work, and discards the rest into a cold body as waste heat. The waste heat is necessary, not an accident of design.
- **C.** The most efficient type of heat engine is a reversible one, pumping heat from a cold object to a hot object, but its efficiency is still less than 100%.

III. German physicist Rudolf Clausius combined previous theories about the conservation of energy with Carnot's observations and proposed the first and second laws of thermodynamics.

- **A.** The first law is the law of conservation of energy. The second law states that it is impossible for heat to flow spontaneously from a hot object to a cooler one.

B. English physicist William Thompson, Lord Kelvin, reframed both laws in terms of impossibility: The first law states that a perpetual motion machine of the first kind is impossible; the second law states that a perpetual motion machine of the second kind is also impossible.

C. Clausius introduced a new version of the second law based on the idea of entropy, or how available an object's energy is for doing work.

D. When heat is added to a body, its entropy increases. For hotter objects, the entropy increase is small; for colder ones, larger.

E. The total entropy of an object and its surroundings can never decrease.

IV. The science of thermodynamics has far-reaching implications.

A. Earth itself may be regarded as a heat engine, absorbing energy from the Sun and radiating it into cold outer space.

B. The temperature difference between the Sun and the rest of the sky provides the energy supply for all life and movement on Earth.

C. The entropy of the universe tends toward thermodynamic equilibrium, or uniform temperature.

D. Helmholtz calls this the heat death of the universe, a far-future state when no more life or activity is possible.

V. Unlike Newton's laws of motion, the second law of thermodynamics gives time a definite direction—the "arrow of time," distinguishing between future and past.

A. In purely mechanical terms, we can "reverse the film" of the universe and everything appears to follow the same laws.

B. However, if we reverse the film, entropy decreases, violating the second law. This provides a basic distinction between future and past.

C. This is related to other arrows of time, including the psychological one—we remember the past but not the future. Other connections, such as to the expansion of the cosmos, are less clear.

Questions to Consider:

1. The 4 main sources of electrical energy in the United States are coal, nuclear, natural gas, and hydroelectric power. Explain how each of these sources either directly or indirectly involves a heat engine.
2. As an experiment on the arrow of time, take a short section of a film or video and view it in reverse. (A car chase from an action movie works well for this.) Which processes in the reversed video look normal? Which ones look strange but possible? Which ones seem to be impossible in reverse?

Lecture Six
Maxwell's Demon

Scope:

In 1867, James Clerk Maxwell introduced his famous "demon": a tiny imaginary being that, by observing and sorting vast numbers of molecules, can reduce the entropy of a system. Could Maxwell's demon really exist as a threat to the second law? Many potential ways of creating such a demon have been proposed, all of them suffering from one or another fatal flaw.

Outline

I. In the 19th century, physicists came to realize that matter is made of atoms and molecules. This helped to explain many aspects of thermodynamics.

- **A.** Atoms in a gas are in ceaseless rapid motion in all directions, and heat is the kinetic energy of this random motion.
- **B.** What prevents the molecules in a container of gas from simultaneously moving in one direction? According to James Clerk Maxwell, a 19th-century physicist, nothing.

II. Maxwell said the second law of thermodynamics is really a statistical law, its violation a statistical, not a physical, impossibility.

- **A.** Maxwell introduced a famous thought experiment, Maxwell's demon: a tiny being that can observe and manipulate individual molecules.
  1. The demon is stationed at a small opening between 2 chambers of gas, operating a door.
  2. When a molecule approaches from one side, the demon opens the door. When a molecule approaches from the other side, the demon keeps the door closed.
  3. Since molecules can only pass one way through the opening, eventually, all the molecules are located on one side, lowering the entropy of the system!

B. Maxwell's demon, by decreasing entropy, could be used to make a perpetual motion machine of the second kind.

1. By reexpanding the gas, the demon can do work while reducing the temperature of the gas.
2. The net apparent result is that heat has been extracted from the gas and turned into useful work.

III. For more than a century, physicists wrestled with the problem of Maxwell's demon.

A. Marian Smoluchowski replaced the demon with a small, spring-loaded trapdoor. Collisions with the molecules would transfer energy to the door, making it bounce open and closed at random. The trapdoor could not work like the demon.

B. Rolf Landauer and Charles Bennett finally distilled Maxwell's demon to its essentials: The demon is a device for obtaining and using information.

1. As the demon operates, it accumulates trillions of trillions of bits of useless information.
2. To continue to operate, the demon must erase its memory. As Landauer showed, any process that erases information must be accompanied by waste heat.
3. The entropy produced by this waste heat—the cost of information erasure—offsets any reduction of entropy created by the demon. The cost of erasure saves the second law.

IV. Maxwell's demon gives us new insight into the meaning of entropy. Entropy is information.

A. The entropy of a system is the amount of information that we lack about its detailed microscopic state.

B. The entropy of a gas is greater if the gas has more energy or occupies a larger volume.

C. Entropy can also be viewed as a measure of disorder—the more orderly a system, the less information we lack.

D. The information acquired by the demon is also a type of entropy.

V. The concept of information was developed by Claude Shannon in the late 1940s to describe the mathematics of communication. Although it was invented for technological applications, it turns out to be a fundamental idea in physics.

Questions to Consider:

1. Does it matter whether Maxwell's demon erases all of its information at the end of its function, or bit by bit as it is acquired?

2. A container has 2 chambers, 1 containing nitrogen gas and 1 containing oxygen gas. The valve connecting them is opened and the gases are allowed to mix. Does the entropy of the gas increase? Explain your answer. What if both chambers contained nitrogen gas?

Lecture Seven
Absolute Zero

Scope:

Absolute zero is the extreme limit of cold, the temperature at which no heat energy is present. It is the starting point of the Kelvin temperature scale, in which absolute zero is 0 K. According to the third law of thermodynamics, the entropy of any object must decrease to zero as its temperature approaches 0 K. In this lecture, we discuss some of the remarkable properties of matter at low temperatures and why absolute zero remains forever out of reach.

Outline

I. Temperature scales were introduced in the 18th and 19th centuries.

- **A.** Ordinary temperature scales have an arbitrary zero point, such as the freezing point of water; an absolute temperature scale starts at absolute zero.
- **B.** The physics of gases suggests that there is an absolute limit of cold at around −273°C, or 0 K, a temperature at which all random molecular motion stops.
- **C.** Consider these Kelvin temperatures versus the scales you are familiar with.

Absolute zero	0 K
Nitrogen boils	77 K
Ice melts	273 K
Room temperature	300 K
Water boils	373 K
Lead melts	600 K
Surface of the Sun	6000 K

II. Throughout the 19th and 20th centuries, experimental physicists produced colder and colder temperatures in the laboratory.

A. More and more gases, including oxygen, nitrogen, and hydrogen, were condensed into liquids.

B. In 1908, Heike Kamerlingh Onnes liquefied helium at a temperature of 5 K. Within a few years, we was able to produce temperatures below 1 K.

III. The basic process of cooling a gas is a sequence of alternating isothermal compressions and adiabatic expansions.

A. In isothermal compression, the gas is held at a constant temperature and slowly compressed.

B. In adiabatic expansion, the gas is expanded while insulated from its surroundings. Since no heat is transferred, the entropy of the gas does not change.

C. On a graph of this process where temperature (t) is the vertical axis and entropy (s) is the horizontal axis, a given constant volume creates a diagonal curve.

IV. The third law of thermodynamics, discovered by Walther Nernst in 1905, prevents any object from being cooled to absolute zero.

A. As temperature approaches zero, entropy also approaches zero. On the diagram described above, all of the constant-volume lines would intersect where $t = 0$ and $s = 0$.

B. The cooling process can never reach absolute zero because it takes horizontal and vertical steps. No finite number of steps can ever get to where the lines meet; thus it is impossible to reach absolute zero.

C. A useful analogy: It is impossible to dry off completely using towels that are slightly damp—you cannot get drier than the towel was when you started. Since everything starts out with at least a little heat energy, no finite process can wring every last bit of heat energy out of anything.

V. Although absolute zero is unattainable, physicists have come extremely close. Along the way, they have discovered some astounding new properties of matter.

A. In 1911, Kamerlingh Onnes discovered that at extremely low temperatures, metals can become superconductors—objects with zero electrical resistance, or electrical friction.

B. In 1937, Pyotr Kapitsa showed that liquid helium becomes a superfluid below 2 K. A superfluid has no viscosity, or flow friction, and perfect heat conduction.

C. At less than one millionth of a degree above absolute zero, a cloud of atoms can form a Bose-Einstein condensate; atoms lose their individuality and behave in a collective, quantum-mechanical way.

D. These new states of matter discovered at low temperatures are the result of quantum effects that can only be seen when there is very little heat energy present.

Questions to Consider:

1. On a piece of paper, draw a line representing an absolute temperature scale. At the ends, mark absolute zero (0 K) and room temperature (300 K). Do a little research to find the following temperatures, and plot them on your scale: The coldest temperature ever recorded near your home; the coldest temperature ever recorded on Earth; the boiling points of ammonia, oxygen, nitrogen, hydrogen, and helium; the highest known temperature for a superconductor; the cosmic background temperature; and the temperature of a typical Bose-Einstein condensate.

2. In a heat-engine cycle, a gas undergoes isothermal expansion at a high temperature, adiabatic expansion to a low temperature, isothermal compression at the low temperature, and then adiabatic compression back to the high temperature. Sketch this cycle as a closed path on an entropy-temperature (*s*-*t*) diagram like the one used in the lecture. (As an interesting aside, the area enclosed by your path is equal to the net work done by 1 cycle of the engine.)

Lecture Eight
Predicting the Future

Scope:

In a deterministic system, knowledge of present conditions enables us to predict how the system will behave into the indefinite future. While in principle, this is true of both 2-body and 3-body systems, in practice, the behavior of the 3-body system may be radically harder to predict. This is the phenomenon of dynamical chaos, which is present in many systems, including the human brain. Even if the future of a chaotic system is mathematically determined, that future may be impossible to predict.

Outline

I. Systems of particles described by Newton's laws of motion are perfectly deterministic.

- **A.** Newtonian mechanics is a deterministic system to describe how forces govern the paths of particles. Specifying the positions and velocities of particles at one time allows (in principle) the motion to be determined at all times.
- **B.** Pierre-Simon Laplace imagined a demon that had complete knowledge of all the locations and velocities of all particles in the universe. Such a demon could in principle predict the future of the universe exactly.

II. Even relatively simple applications of Newton's laws defied mathematical solution for centuries.

- **A.** The motion of a 2-body system is simple, but the motion of a 3-body system is too complex to determine.
- **B.** Henri Poincaré attacked the 3-body problem with new methods in 1887, glimpsing signs of extremely strange and complex behavior in such systems.

III. Edward Lorenz stumbled on the concept of chaos while performing numerical experiments on weather forecasting.

A. Lorenz's highly simplified model of the weather showed unexpected results: The system showed sensitive dependence on initial conditions.

B. Lorenz soon found this behavior in waterwheels as well. Starting the wheel with slightly different conditions will lead to different long-term behavior.

C. Sensitive dependence on initial conditions means that the system is fundamentally unpredictable, or chaotic.

1. We always are slightly uncertain about any system's initial conditions. Thus we can only predict the future behavior of the system for a short time.

2. Lorenz called this the butterfly effect. The motion of the wings of a butterfly in Brazil can determine whether or not there are tornadoes in Texas a month from now.

3. We can therefore only make predictions about these systems in general terms—that is, we can predict climate, but not weather.

IV. Lorenz's discovery led to a new science of chaotic systems.

A. In chaotic systems, more precise knowledge of initial conditions does not help much in making predictions.

B. Chaotic systems are found all over nature, in everything from the 3-body problem to bouncing balls to the function of the brain. All of these systems have sensitive dependence to initial conditions; all of them are fundamentally unpredictable.

C. Chaos makes Laplace's demon impossible: To make exact predictions of the future, the demon would have to know all positions and velocities to an infinite number of decimal places—an infinite amount of information!

D. All real creatures in the universe can possess only a finite amount of information. Since the universe contains chaos, this limits their ability to predict the future.

E. Whether or not the universe is actually deterministic, for inhabitants of the universe, it is unpredictable.

Questions to Consider:

1. This lecture is about the difference between determinism and predictability. Do you regard this difference as fundamental, or merely incidental? Why?
2. Imagine 3 physical systems. System 1 follows deterministic laws and has regular (nonchaotic) motion. System 2 follows deterministic laws but has chaotic motion. System 3 follows nondeterministic laws—that is, its motion involves actual randomness. In what ways are systems 1 and 2 alike? In what ways are systems 2 and 3 alike?
3. Chaos makes exact prediction of the future impossible, even for a deterministic system. Recalling the 3 types of impossibility from Lecture One, which type of impossibility is this?

Lecture Nine
Visiting the Past

Scope:

Time travel into the future is relatively easy. Time travel into the past, however, is impossible. The basic problem, familiar from the grandfather paradox and the telegraph paradox, is a causal loop, a chain of cause and effect that forms a closed circle. The paradoxes of time travel are so fundamental that most physicists regard time travel as a near-absolute impossibility. Yet science fiction writers—and a few imaginative physicists—have proposed ways to avoid the paradoxes of time travel. We explore some of these rather unsettling ideas.

Outline

I. The second law of thermodynamics gives a direction to time, differentiating past and future.

- **A.** The future is the direction of higher entropy.
- **B.** This arrow of time is probably related to our sense of time (our psychological arrow).
- **C.** Memories are formed by a biochemical process that increases entropy. Our memories record only the past, not the future.
- **D.** Our ability to predict the future of a chaotic system is limited; long-term prediction is impossible.

II. Is time travel into the future possible? There are several possible methods.

- **A.** Biological stasis or hibernation may be possible.
- **B.** At least 2 possibilities involve relativity: travel at near light speed and cozying up next to a black hole.

III. Time travel into the past is impossible.

- **A.** The grandfather paradox and the telegraph paradox are common ideas from science fiction that describe why neither people nor information can travel to the past.
- **B.** Physicists call this problem a causal loop because it breaks the chain of cause and effect.

C. The only way around these paradoxes is to assume either that we would not be free to use a time machine as we wished, or we would not be able to act as we wished if we used it—that is, free will is an illusion.

D. It is simpler to assume that the laws of nature are such that a time machine can never be built.

IV. These paradoxes assume that only one thing can happen from an action: shoot or do not shoot, send a "yes" message or send a "no" message. What if both things happen?

A. This idea is sometimes called many-branching time. When we create a paradox, we are actually experiencing or communicating with a different branch of time where events occurred differently.

B. Time-branching theory has similarities to a major school of quantum theory, the many-worlds interpretation, but we cannot say that quantum theory allows time machines to exist.

V. The arguments against the possibility of time travel are very strong, but we use the impossibility of time machines as a basis for thinking about time, information, and cause and effect.

Questions to Consider:

1. Time travel is a very common theme in science fiction. Make a list of films and TV shows you have seen that use this theme. How does each of them approach the grandfather paradox?
2. What is the role of free will in the thought experiments leading to various time-travel paradoxes?

Lecture Ten
Thinking in Space-Time

Scope:

Einstein's special theory of relativity is best understood as a theory of space-time, the 4-dimensional world that forms the arena for all of physics. In space-time, the universe does not "happen"; past, present, and future simply are. Observers divide space-time into space and time coordinates, and different observers do this in different ways. Two events that are simultaneous for one observer may not be simultaneous for another observer.

Outline

I. Albert Einstein's theory of relativity was a revolution in physics, redrawing the boundary between the impossible and the possible.

A. Many aspects of the theory may sound impossible, but all of them have been confirmed by experiment.

B. To understand the theory, we must think of the universe as having 4 dimensions—3 of space and 1 of time.

II. Einstein proposed relativity to solve the mathematical inconsistency between Isaac Newton's mechanics and James Clerk Maxwell's electrical and magnetic field equations.

A. Maxwell described light as a wave, a traveling disturbance in an electromagnetic field.

B. Maxwell's equations require an absolute speed of light, c—namely, 300,000 kilometers per second.

C. Newton's mechanics predict that an observer in motion would observe a different light speed, and almost everyone, including Maxwell, thought this was correct.

D. However, in the 1880s, Albert Michelson and Edward Morley performed a super-sensitive optical experiment and found that light speed was observed as an absolute, no matter how fast the observer moved.

III. Einstein's radical solution to this problem was that Newton's theory needed to be altered.

A. Relativity states that space and time measurements are relative to an observer.

B. The fundamental laws of physics are the same for all observers—that is, the speed of light remains constant.

C. There is nothing special about light per se; it is one of many things that moves at this fundamental speed.

IV. Hermann Minkowski realized that Einstein's theory was really about the relationship between space and time.

A. Space is 3-dimensional: latitude, longitude, and altitude specify where an event takes place.

B. To specify the "when" of an event, we need a fourth dimension, time.

C. Everything that happens in the universe can be located by these 4 coordinates.

V. How can we visualize 4-dimensional geometry? We simplify.

A. The standard space-time diagram is 2-dimensional, with space on the horizontal axis and time on the vertical axis.

B. Space is measured in meters; time is converted to meters by multiplying it by c. A meter of time = 3×10^{-8} seconds.

C. We call a point in space-time an event.

D. A moment in time consists of all points in space at a particular time; space-time is a stack of these moments, like stacking up all the frames of a film into a solid block.

E. The movement of a particle through space-time creates a world line, stretching from past to future.

1. If the particle at rest makes a straight up-down world line on a graph.

2. A particle in uniform motion makes a straight diagonal world line.

3. An accelerating particle makes a curved world line.

4. A particle moving in a circle makes a helical world line.

5. When particles collide, their world lines meet and bend.

F. The movement of a larger object, such as a planet, creates a thicker world line, sometimes called a world tube.

VI. From the space-time point of view, events do not happen; they simply are.

A. Picture effects moving outward from an event, like ripples from a stone thrown into a pond.

B. In space-time, the circles are stacked up into an object called a light cone. The point of the cone is the event, and the effects move outward at a 45 degree angle (1 meter of space per 1 meter of time).

C. When an observer witnesses an event, we say the observer's world line intersects the light cone.

D. If you extend the point of a light cone into the past, you include all events from which light reaches the point.

VII. Einstein came to agree with Minkowski's interpretation of relativity, calling the passage of time an illusion. Physics needs an "eternal" point of view, outside time.

VIII. What about this business of different observers—the relativity in relativity? Consider Alice, at rest, and Bob, moving to the right.

A. From Alice's perspective, her world line is vertical, and Bob's is tilted to the right. From Bob's perspective, his is vertical and hers is tilted to the left.

B. Their diagrams look a little different, but they represent the same space-time. Different observers assign different space and time coordinates to events.

C. Events that are simultaneous for one observer may not be so for another. This resolves many seeming paradoxes of relativity.

Questions to Consider:

1. A particle moving to the right collides with another particle at rest. The particles stick together, moving to the right somewhat more slowly than the first particle did. Sketch a space-time diagram for this process.

2. The Sun is so far away from Earth that it takes about 8 minutes for light to travel from one to the other. Explain why the phrase "What is happening right now on the Sun" is in fact slightly ambiguous when used by an earthling.

3. Given 2 events A and B in space-time, we can write $A \rightarrow B$ to mean that event B lies within the (future) light cone of A. If B is outside the light cone of A, we write $A \nrightarrow B$ instead. Draw space-time diagrams that illustrate the following possibilities:

(a) $A \rightarrow B$ but $B \nrightarrow A$.

(b) $B \rightarrow A$ but $A \nrightarrow B$.

(c) $A \nrightarrow B$ and $B \nrightarrow A$.

Lecture Eleven

Faster than Light

Scope:

Another staple of science fiction is faster-than-light travel. Such a hyperdrive would be convenient for traversing the light-years between stars, but could it exist? According to relativity, it is impossible for a thing to travel faster than the speed of light. But what exactly is meant by a "thing"? By considering various thought experiments, we conclude that the ultimate speed limit applies to information.

Outline

I. According to relativity, the speed of light, c, is the ultimate speed limit of the universe.

- **A.** If a spaceship cannot travel faster than the speed of light, it will need years to travel between the stars.
- **B.** We say that "nothing" can travel faster than light, but what do we mean by a "thing"?

II. Light travels at c in empty space but more slowly through a medium, because it interacts with atoms in the medium.

- **A.** In water, waves of visible light travel at only 75% of c. But it is possible for particles to travel through the water faster than 75% of c.
- **B.** Charged particles going through a medium slower than c, but faster than light, produce Cherenkov radiation, named for Pavel Cherenkov, a Russian physicist.

III. Can we conceive of something that goes faster than c?

- **A.** Imagine 2 straight edges overlapping at a thin angle like the blades of a pair of scissors.
- **B.** If you open the blades at a speed just slower than c, their point of intersection scoots sideways, maybe faster than c.
- **C.** Of course, the point of intersection is not really a thing. It is a geometric relationship.

D. Imagine instead a pulse of light sent down an empty tube at speed *c*. The pulse would appear brightest (and have the most energy) in the middle and would be dimmer at the ends.

E. Add a transparent medium to the tube and send another pulse: The second pulse travels at a slower speed, lagging behind the first.

F. The pulse bunches up; an initial wide pulse becomes a narrow pulse, and the center of the emerging pulse arrives ahead of the first pulse—the light goes faster than *c*!

G. How have we violated the speed limit?

1. There is a sense in which the emerging pulse is not the same energy. The medium absorbs and emits energy as the pulse passes.
2. More importantly, the center of the pulse arrives faster because the pulse gets narrower. The leading edge of the pulse never goes faster than *c*.
3. What is at the leading edge? The news that a pulse is coming. It contains the information.

IV. The real principle at work is that it is impossible for information to travel faster than the speed of light. To find out why, we need to dig a little deeper into the theory of relativity.

A. One important effect of relativity is time dilation—simply stated, a moving clock runs slowly.

B. Time dilation affects everything, not just wristwatches: Moving atoms and molecules vibrate more slowly, unstable particles last longer, and even the biochemical processes of the body slow down at speeds close to *c*.

C. In the space-time view, the ticks of a clock are events along its world line. A moving clock's ticks appear more widely spaced on a graph.

V. How does time dilation apply to the speed of information?

A. Imagine Alice is at rest and Bob is traveling near *c*, such that Alice's clock appears to run twice as fast as Bob's.

B. If Alice could send Bob a signal that traveled faster than *c*, it would appear to Bob that her signal was going backward in time.

C. When Bob replied to Alice, his signal would reach Alice before she sent the original message. Thus Alice could use Bob as a relay to send a message into her own past.

D. Because we know this would create a time telegraph paradox, we know sending messages faster than light is impossible.

E. This exercise demonstrates the link between "faster than light" and "backward in time." Since any object carries information (even simply "here comes the object"), no object can travel faster than light.

VI. The conventional idea of time is a line, where "now" is a point on the line with "the future" on one side and "the past" on the other.

A. In space-time, now is a point on a graph, and my world line passes through it.

B. Because I cannot go faster than light, the future of my world line must lie inside the light cone of the present event.

C. The light cone thus contains all the parts of the universe I can visit, all events in the universe that I can affect.

D. In the same way, the only past events that could have an effect on here-and-now lie in the event's past light cone.

VII. The light-cone structure is fundamental to the theory of relativity.

A. It tells us which events can influence which other events.

B. It demonstrates the causal structure of space-time.

C. It controls how objects and information can move in space-time.

Questions to Consider:

1. Think of some events that are (a) within your future light cone, (b) within your past light cone, and (c) outside of either. Which events can you (in principle) influence? Which could have had an influence on you?

2. Suppose that different observers can launch spaceships that can travel faster than light. Show how to use such spaceships to create a grandfather paradox.

Lecture Twelve
Black Holes and Curved Space-Time

Scope:

The general theory of relativity treats gravity as a warping of space-time. The most extreme case is that of a black hole, which has a spherical event horizon surrounding a central, point-like singularity of enormous gravity. Light cones are tilted in the vicinity of a black hole so that no messages can ever escape from inside the event horizon. To understand this, we imagine a probe falling into a black hole from both the probe's perspective and ours.

Outline

I. We established that, no matter which direction I travel, no matter how fast I go (up to *c*), I cannot bend my own world line enough to get outside the light cone of my future.

- **A.** Since this future light cone continually expands, this does not seem like such a terrible trap.
- **B.** In this lecture, we discuss a different and less innocuous sort of trap: a black hole.

II. A black hole is object whose gravity is so strong that nothing inside its event horizon—even light itself—can ever escape.

- **A.** The existence of black holes was predicted more than 200 years ago by Pierre-Simon Laplace.
- **B.** Laplace was using Newtonian mechanics and assuming that gravity could affect light, which is now known to be true.
- **C.** If light cannot escape such intense gravity, then the most massive objects in the universe might be invisible to us.

III. Escape speed is the speed at which an object must be launched from a planet so that the object is never pulled back to the planet's surface.

- **A.** For Earth, this speed is 11.2 kilometers per second.
- **B.** For a black hole, we would think escape speed must be greater than *c*, but it turns out to not be quite so simple. Newton's theory is not quite right for extremely strong gravity fields.

IV. The way Albert Einstein's special theory of relativity describes space-time is a bit like how a flat map shows Earth's surface.

A. Within a small area—like a county—a flat map can be quite accurate.

B. For much larger areas—like a continent or a hemisphere—the flat map is more distorted, because the map squashes a curved surface into a flat one.

C. Special relativity works well for small regions of space-time but not for larger ones, because space-time is actually curved.

V. The curvature of space is an effect of gravity.

A. Curvature is produced by mass, and it affects how objects move through space-time—that is, it affects the shape of world lines.

B. The general relativity equations, which relate mass and curvature, were proposed by Einstein but were solved by Karl Schwarzschild.

C. Schwarzschild's solution described the warped space-time around a massive object of zero size. That same math will describe the space-time around any spherical mass.

D. Schwarzschild's point mass was originally viewed as a mathematical convenience, but now it is taken very seriously.

VI. In the 1930s, astrophysicists began to ponder what happens to a massive star at the end of its life.

A. A star is a massive ball of gas that produces energy in its core via nuclear reactions. This energy keeps the star inflated so that the star does not collapse under its own mass.

B. When the fuel in the core is exhausted, a very massive star can form a neutron star, a small but extremely dense object.

C. If the initial mass is great enough, the gravity is so strong that the star collapses into a point mass called a black hole.

VII. The distortion of space-time around a black hole is extreme and affects the structure of nearby light cones.

A. Near a point mass, light cones are tilted slightly toward the mass. The closer the mass, the greater the tilt.

B. Up to a point, light can go toward the mass or away from it, but at the event horizon, light is entirely tilted toward the mass.

C. The event horizon is visualized as a spherical surface around the point mass. Note, however, that it is not a physical surface, just a mathematical borderline.

VIII. What happens when an object falls through this mathematically defined surface and emits a flash of light?

A. All the light emitted in all directions is bent inward, toward the central point mass.

B. No light information can ever return to the outside world, because the light cone is entirely within the event horizon. The geometry of space-time hides the event from us.

IX. What would an outside observer see when an object falls into a black hole?

A. Imagine a probe that transmits regular radio signals being launched toward a black hole.

B. First, we see the probe fall inward, accelerating toward the hole.

C. As the probe approaches the event horizon, it appears to slow down. Similarly, the time between each of the probe's signals seems longer and longer.

D. The light from probe rapidly dims and shifts toward the red, until the probe finally fades from our view just outside the event horizon. The radio signals finally cease.

X. What happens from the probe's point of view?

A. Time appears to progress normally as the probe crosses the event horizon quickly and easily.

B. There is nothing to mark the event horizon; it is not a tangible surface, although it is the point of no return.

C. Because of the extreme curvature of space-time near a point mass, gravity is much stronger at the probe's nose than at its tail. Tidal forces begin to pull the probe apart.

D. The probe is pulled inexorably toward the mass at the center, a point of infinite density and infinite space-time curvature.

E. This point is called a singularity, a kind of cusp or edge to the universe of space-time.

F. The probe is sucked into the singularity and destroyed, not because of the gravitational force but because of the extraordinary distortion of space-time.

XI. If we cannot see black holes, how do we know they really exist?

A. Matter being pulled into a black hole is compressed and heated before crossing the horizon. This can be detected as a rapidly fluctuating X-ray source.

B. The gravity of a black hole affects the motions of nearby objects, so its presence can be inferred from their behavior.

XII. Note, the view of black holes presented here does not take quantum physics into account.

A. We still do not have a well-understood, generally accepted quantum theory of gravity.

B. If light cones can be bent by black holes, maybe they can be bent in an even more radical way.

C. Perhaps we can use curved space-time as a short cut and evade the apparent limitation of the speed of light, or, more disturbingly, twist the light cone structure around to make causal loops! Are warp drive and time travel possible after all?

Questions to Consider:

1. Imagine a project to send a space probe into a black hole. Someone suggests sending a second probe just behind the first one to act as a communication relay to the outside world and thus get data from inside the black hole. Explain why this would not work.
2. In what sense is the event horizon the surface of a black hole? Is anything really there?

Lecture Thirteen
A Spinning Universe, Wormholes, and Such

Scope:

Kurt Gödel used Albert Einstein's theories to propose a very strange and startling model of the universe that allows for closed causal loops. Time travel, far from being forbidden by Einstein's relativity, might be possible after all—at least in some peculiar kinds of universe. This discovery led to other research on the weirder consequences of Einstein's theories, including wormholes. Causal loops and wormholes do not appear to exist in our universe, yet they remain tantalizingly close to the border between the possible and the impossible.

Outline

I. If we had a way of sending information faster than light, we could send information into the past, which would allow us to set up causal loops.

- **A.** In a causal loop, *A* causes *B*, which causes *C*, which causes *A* in the first place, even though it happened after *A*.
- **B.** Because this is a paradox, we consider it impossible.
- **C.** However, what if warping the geometry of space-time could warp the very structure of cause and effect?

II. In ordinary space-time, an event can eventually have an effect on any point in space inside its light cone, if you wait long enough. But near a black hole, this is not the case.

- **A.** An event inside a black hole can never have an effect outside the event horizon.
- **B.** If the structure of cause and effect can thus be bent by gravity, could we bend it into a circle and create a causal loop?

III. Do Einstein's equations, the basic rules for matter and space-time geometry, allow for a closed timelike curve—that is, a world line that permanently stays inside its light cones?

- **A.** Mach's principle, named for Austrian physicist Ernst Mach, said that distant masses in the universe actually determine local inertia, perhaps by some gravitational effect.

B. Einstein, inspired my Mach's principle, suggested a relation between inertia and gravity.

C. The Lense-Thirring effect, named after Austrian physicists Josef Lense and Hans Thirring, suggests that the spin of objects around you "drags" your sense of rotation (inertia) around with it very slightly.

D. Kurt Gödel, an Austrian mathematician, invented a theoretical universe that follows the rules of relativistic space-time, but the entire universe is also rotating.

E. In this universe, in the middle of a space-time diagram, the light cones look normal, but to each side of the central world line, the light cones are twisted. The further you go from the center, the greater the twist.

F. This has shocking consequences. It implies that a light cone can return to its origin, not only in space but in time—a closed timelike curve.

G. Our best observations to date indicate that our universe is not rotating, yet Gödel's universe is a possible one.

IV. The current view of wormholes was developed when astronomer Carl Sagan asked physicist Kip Thorne about an idea Sagan had for his novel, *Contact*.

A. Sagan wanted to use the idea about space-time shortcuts, or bridges, proposed by Albert Einstein and Nathan Rosen.

B. Sagan asked Thorne if Einstein-Rosen bridges (a.k.a. wormholes) could exist, but Thorne said no. They collapse into black holes too quickly.

C. Sagan then asked if there was way to prevent the wormhole from collapsing. Thorne decided to work on it.

D. Thorne calculated that to prevent collapse, you had to stuff the wormhole with exotic matter, matter with negative energy.

E. We do not know whether exotic matter exists. All matter we know of has positive energy.

F. Quantum physics indicates that small regions of space might have a little negative energy, but exotic matter in bulk does not seem to be available.

V. A pair of connected wormholes would create a closed timelike curve and thus create a time machine. But how could we create a wormhole?

A. It is most likely impossible to make a wormhole from scratch, but tiny ones may exist in nature as remnants of the big bang.

B. To make it usable, we would have to find one, vastly enlarge it, and stabilize it on both ends with exotic matter.

C. Even if this were doable, we have reason to believe a real wormhole would be surrounded by powerful quantum radiation. Any information sent into one end would be totally scrambled before it came out.

VI. Mexican physicist Miguel Alcubierre has proposed an alternative to wormholes that is strongly reminiscent of *Star Trek*'s warp drive.

A. On Alcubierre's diagrams, a tube cuts across space-time.

B. Outside the tube, the cones are normal; inside, they are tilted.

C. You cannot travel faster than light inside or outside the tube, but matter inside the tube seems to move faster than light: Space contracts in front of it and expands behind it.

D. Unfortunately, this setup also requires negative energy.

VII. Stephen Hawking has proposed the chronology protection conjecture: The laws of nature are set up to prevent time travel. Understanding how will involve a new and deeper understanding of the nature of space and time, information, and cause and effect.

Questions to Consider:

1. A Foucault pendulum swings back and forth in a plane, but that plane appears to slowly precess because Earth rotates beneath it. Does this count as an eyes-open or eyes-shut way of detecting Earth's rotation?

2. The various ideas for creating causal loops—Gödel's universe, wormholes, and so on—all appear to be impossible. The universe as a whole does not seem to rotate, and we know of no form of negative-energy matter that could stabilize a wormhole. Are you satisfied? Why or why not?

3. Do you think Hawking's chronology protection conjecture is true?

Lecture Fourteen
What Is Symmetry?

Scope:

A symmetry is any transformation that leaves a shape or a physical system unchanged. It expresses a kind of impossibility: For a symmetric figure, it is impossible to tell whether the given transformation has been applied to it. The "before" and "after" forms are exactly the same. Some of the deepest principles of physics are best expressed as statements about symmetry.

Outline

I. The concept of symmetry is as fundamental as time, information, and causation in drawing a line between the possible and the impossible.

- **A.** We know what it means to say a geometric shape is symmetrical: A mirrored or flipped shape is identical to the original.
- **B.** Formally, symmetry is defined as invariance under transformation; *x* is symmetric if it is impossible to tell whether or not a given transformation has been applied to *x*.
- **C.** Symmetry can apply to patterns as well as shapes, as in a pattern of tiles on a floor.
- **D.** In physics, we apply the concept of symmetry to the laws of nature.

II. What does it mean to say that a law of nature has a symmetry?

- **A.** Given a situation, a law allows us to predict the behavior of a system.
- **B.** Given a possible transformation of a system, the law is symmetric if the original and transformed situations have exactly the same behavior.
- **C.** Translation symmetry means that there is no location in space with special properties—laws work the same everywhere.
- **D.** Exchange symmetry says all particles of a certain type (electrons, protons, etc.) are identical to others of that type.

III. German mathematician Emmy Noether, a contemporary of Albert Einstein, declared that every symmetry of the laws of physics leads to a conservation law, and every conservation law arises from a symmetry of the laws of physics.

A. The most surprising of the many symmetries of nature is translation in time. The laws of nature apply equally at all times.

B. Why is this surprising? It means that it is impossible to tell what time it is in absolute terms.

C. Noether thus argued that, because of this symmetry, it is impossible to build a perpetual motion machine of the first kind.

D. Noether's theorem, originally proved in the context of classical, Newtonian physics, works even better in quantum theory.

IV. The laws of physics also have some approximate symmetries associated with approximate conservation laws.

V. Ultimately, this principle of symmetry allows us to hold a mirror up to theoretical universes and see whether it is possible to distinguish them from our own. In that way, we learn more about the laws of our own universe.

Questions to Consider:

1. Write down the capital letters of the Roman alphabet (A, B, etc.) and divide them into categories based on the different symmetries of their shapes.

2. Find an attractive fabric or wallpaper pattern and describe its symmetries. These symmetries may involve translation in space, reflections, rotations, or combinations of all 3.

3. Explain in your own words why a lecture on symmetry is part of a course on the physics of impossible things. You should be able to give at least 2 reasons.

Lecture Fifteen
Mirror Worlds

Scope:

By imagining various kinds of reflected worlds, we can understand some of the basic symmetries of physics. Parity symmetry exchanges left and right; charge conjugation exchanges matter and antimatter (positive and negative); and time reversal exchanges future and past. Surprisingly, the combination of all 3 mirrors—parity, charge, and time—does appear to be an exact symmetry of the laws of nature.

Outline

I. We examine 3 fundamental symmetries, or mirrors, of our universe—reflections in space, matter, and time—and ask whether it is possible to tell the world in the mirror from our own.

- **A.** If it is impossible, then the mirror represents a basic symmetry of nature.
- **B.** If it is possible, then nature is not symmetric in that way, and the change matters to the laws of nature.
- **C.** This lecture touches on some of the most unexpected discoveries in the history of physics and includes a clue to a basic puzzle about the cosmos—namely, how atoms could exist.

II. Our first mirror reflects space, exchanging left and right. Physicists call this parity.

- **A.** Our universe was long assumed to possess parity. Newton's laws of motion and the laws of electromagnetism work exactly the same way in the reflected world.
- **B.** In 1956, Chen Ning Yang and Tsung-Dao Lee realized that the nuclear forces—in particular, the force responsible for beta decay—make a fundamental distinction between left and right.
- **C.** Their theory was later confirmed by Chien-Shiung Wu: Beta decay almost always emits particles in one direction (i.e., asymmetrically), following a right-hand rule.

III. The next mirror is not a reflection in space but in the properties of matter, called charge conjugation.

A. This mirror turns matter into antimatter, and vice versa.

B. Antimatter was predicted in 1927 by English physicist Paul Dirac, who was trying to reconcile relativity and quantum theory.

C. Antimatter is made of antiparticles—particles of the same mass but opposite electric charge to the particles in the matter we know.

D. Dirac's prediction was confirmed when positrons, of the same mass but opposite charge as electrons, were discovered in 1932 by Carl Anderson.

E. Why matter is so common and antimatter is so rare is actually a profound mystery.

F. What would an antimatter universe look like? It would look pretty much the same as our universe. Positrons would repel positrons just like electrons repel electrons, and so forth.

G. However, charge conjugation is not an exact symmetry. As with parity, the direction of beta decay is flipped.

H. However, if you combine parity and charge conjugation—in other words, flip the universe twice, beta decay looks symmetrical again!

I. One asymmetry that remains in this double-flipped universe has to do with rare particles called K-mesons. The combination of these laws is almost, but not quite, a symmetry.

IV. The third and final mirror is time transformation—exchanging future and past.

A. It does not seem possible that this is a symmetry, thanks to the second law of thermodynamics, the arrow of time.

B. However, the second law is always about huge numbers of particles, and it is only a statistical law—entropy decreasing is not strictly impossible, only incredibly unlikely.

C. When 2 similarly charged particles approach each other, at a certain point they repel and fly apart. Run the process backward, and it looks exactly the same.

D. No one is quite sure how to solve this paradox: The universe seems to have time-symmetric laws, but its large-scale behavior is not at all the same in the time mirror.

V. Together, relativity and quantum theory imply that the combination of all 3 mirrors must be an exact symmetry of nature.

Questions to Consider:

1. The spaceship in the science fiction movie *Doppelgänger* visits a version of Earth that was reflected in the parity mirror. Suppose instead it had visited a version reflected in the charge-conjugation mirror. What would happen?

2. Imagine that we are in radio communication with an alien civilization in a distant planetary system. Could we determine simply by exchanging verbal messages whether or not the alien planet was made of antimatter? Why or why not?

Lecture Sixteen
Invasion of the Giant Insects

Scope:

A change of scale is a geometrical symmetry; large triangles have the same properties as small ones. Yet an enlarged or reduced copy of a real object is not the same and does not have the same properties as the original. The reason for this was discovered by Galileo: the square-cube law. The failure of scale symmetry is due to the physics of atoms, which have a definite size. This determines the properties of materials and sets a fundamental scale for the universe.

Outline

I. In this lecture, rather than reflecting the world, we magnify it and ask whether large objects behave the same way as small objects in our universe.

II. The square-cube law, describing how size affects the physical properties of objects, was first discovered by Galileo Galilei and published in his book *Two New Sciences*.

- **A.** The second "new science" concerned strength of structures.
- **B.** Galileo noticed a difference between the basic designs of small and large animals—not just in size but in proportion.
- **C.** He realized the strength of an object is proportional to cross-sectional area, whereas its weight is proportional to volume.
- **D.** Area and volume depend on size in different ways; area is a square (x^2), and volume is cubic (x^3). So the relation of strength to weight is different for objects of different size.
- **E.** This explains why science fiction concepts like giant mutant ants are impossible: Their structures (areas) cannot support their weight (volumes). We see this in real life.
  - **1.** Larger animals lead more sedate lifestyles than smaller ones because they are structurally more delicate.
  - **2.** Larger animals have thicker proportions. Compare the legs of an elephant to those of an ant.

3. Larger animals have lower metabolic rates than smaller ones, using fuel more efficiently.

III. The square-cube law is a general principle of physics. It applies to any structure, not just living things.

A. A lump of coal burns at a moderate rate, but coal dust suspended in air can cause an explosion. The greater surface area of the dust allows greater combination with oxygen from the air and a greater release of energy.

B. The interior of Earth is as hot as the Sun's surface due to radioactive decay of potassium-40. A single Earth rock containing potassium-40 cannot heat itself very well, but the surface-to-volume proportions of Earth are so much larger, it creates a tremendous amount of heat with the same percentage of potassium-40.

IV. Because of the square-cube law, magnification is not a symmetry of nature. Why does nature work this way?

A. Two objects, one large and one small, made of the same materials behave in different ways *because* they are made of the same material, not in spite of it.

B. If you create giant ant, you can not build it out of giant atoms; atoms of each element have a definite, absolute size.

C. What determines the size of an atom and sets the size scale of the universe? Quantum physics.

Questions to Consider:

1. Near the end of the science fiction novel and film *The Incredible Shrinking Man*, the titular man is the size of an insect. What physiological problems would such a man face?
2. The light from the Sun exerts a very small pressure on objects in our solar system. This force pushes tiny dust grains entirely out of the solar system and may cause small long-term changes in the orbits of small asteroids but is completely negligible for big planets. Explain how the same effect has such different consequences on bodies of different sizes.

Lecture Seventeen
The Curious Quantum World

Scope:

Between 1900 and 1930, physics underwent a major revolution with the rise of quantum mechanics, the strange new physics of atoms and particles. Quantum mechanics changed the accepted boundary between the possible and the impossible in unexpected ways. We discuss the origin of quantum mechanics and sketch out a few of its seemingly paradoxical ideas.

Outline

I. Quantum physics is the physics of the microscopic world, the physics of atoms and photons and the elementary constituents of matter.

- **A.** Quantum physics determines the sizes of atoms and the fundamental units of energy, which sets the fundamental scale of nature.
- **B.** In the entire history of modern science, quantum physics is the most wholesale revision of our ideas of the impossible.
- **C.** Quantum theory was devised by physicists struggling to explain experimental facts that seemed on the basis of classical physics to be almost impossible.

II. During the 19th century, physicists built up a very successful picture of the world based on Newton's laws of motion, thermodynamics, and electromagnetism.

- **A.** They knew that matter is composed of tiny atoms, although they could not yet measure their size.
- **B.** They considered light a wave—a moving, oscillating disturbance of an electromagnetic field.

III. Around 1900, this picture began to fall apart.

- **A.** German physicist Max Planck wondered about the relationship between heat and light.
- **B.** If light is a wave, he reasoned, then it should be able to have any strength—any amount of energy—yet it cannot.

C. Planck was forced to suppose that the energy of light comes in indivisible units—quanta. Light is a wave, but it acts like it is made up of particles, which he called photons.

D. He determined that the energy of the photon (E) is related to the frequency of the light wave (f): $E = hf$, where h is an extremely tiny number known as Planck's constant.

E. Ordinary light contains trillions and trillions of photons. Billions of photons are entering your eyes each second.

IV. Albert Einstein read Planck's idea and realized it could explain a major mystery of physics—the photoelectric effect.

A. If we shine a light on a metal surface, electrons are ejected. Brighter light ejects more, but not more energetic, electrons.

B. Einstein realized that the energy of the electrons is determined not by the light's brightness but by its color—its frequency. Higher frequencies produce higher-energy electrons.

C. This seems impossible if light is a wave. But it makes sense if we think of light as a stream of photons. Each photon gives its energy to one electron.

V. After Einstein's work, quantum ideas began to spread throughout physics. Physicists realized these strange ideas apply to matter as well.

A. Danish physicist Niels Bohr suggested that quantum ideas determine the inner structure of atoms.

B. According to 19^{th}-century physics, orbiting electrons should radiate energy away, spiral inward, and collapse.

C. Bohr said that electrons can only orbit a nucleus at certain discrete distances determined by h. The lowest-energy electron has a minimum distance from the nucleus, so the atom cannot collapse.

D. This idea, with some refinement, explains a lot of atomic properties, including the size of atoms.

VI. French physicist and aristocrat Louis de Broglie realized that the particles of matter can also have wave properties.

A. This gives a more definite picture of Bohr's orbits: They represent stationary wave patterns for an electron in an atom.

B. The old 19th-century distinction—matter is made of particles, light is a wave—completely broke down. In the quantum world, light and matter both have wave and particle characteristics.

VII. Between 1900 and the mid-1920s, physicists extended quantum theory to a wider and wider range of phenomena.

A. Things that were once thought to be smooth and continuous turned out to be discrete and discontinuous.

B. Things that were once thought to be discrete turned out to have continuous wave properties.

C. All sorts of quantum phenomena were related to h. Because h is so very tiny, quantum phenomena occur in the microscopic realm.

D. Despite these successes, not until 1925–1926 did a systematic, mathematical quantum theory emerge.

VIII. Austrian physicist Erwin Schrödinger and German physicist Werner Heisenberg developed what looked like completely different quantum theories, but they turned out to be different mathematical forms of the same mechanics.

A. Quantum mechanics is the most successful theory of physics ever created, explaining the nature of light, the structure of matter, and the behavior of particles.

B. The main features of quantum mechanics are wave-particle duality, indeterminism, and entanglement.

C. These 3 basic features take us to some remarkable places.

Questions to Consider:

1. Because Planck's constant (h) is so small, we sometimes say that quantum physics is only important in the microscopic realm. But of course this is not really true. Think of several large-scale facts about the world that are determined by quantum physics.
2. Suppose I generate a "random" number by rolling a cubical die. Is this the type of real randomness associated with quantum physics? If not, what sort of randomness is it?

Lecture Eighteen
Impossible Exactness

Scope:

In Newtonian physics, both the position and velocity of a particle can be specified to any level of precision. Not so in quantum mechanics, where these are limited by Heisenberg's uncertainty principle. A quantum particle simply does not have both a definite position and a definite momentum. In the same way, no process can occur at a definite time with a definite energy. This indeterminacy principle has many important consequences.

Outline

I. How is it that we can learn exactly where a quantum particle is, or where it is going, but not both at the same time?

- **A.** Recall Laplace's demon—an imaginary being who knows the present position and velocity of every particle in the universe.
- **B.** By applying Newton's laws of motion, the demon should be able to perfectly predict the future.
- **C.** However, even a fairly simple system may be impossible to predict, because chaos makes even a deterministic system unpredictable.
- **D.** The same is true on the particle level, not because of chaos, but because of uncertainty, a fundamental aspect of quantum mechanics.

II. The uncertainty principle was discovered by Werner Heisenberg soon after quantum mechanics was invented.

- **A.** Imagine a particle moving along a line—motion in one dimension—and call its position on the line x.
- **B.** The particle moves with a certain velocity v.
- **C.** Its momentum, p, is determined by its mass times its velocity: $mv = p$.
- **D.** In Newtonian physics, the particle always has a definite position in space and a definite momentum.

E. However, a quantum particle is described by probabilities; rather than definite values for x and p, there is a range.

F. We express this as Δx, uncertainty in position, and Δp, uncertainty in momentum. Their product is always greater than Planck's constant: $\Delta x \Delta p > h$.

G. The more precisely we know x, the less precisely we can know p, and vice versa.

III. Planck's constant, which determines the size of quantum effects, is extremely tiny: 6.63×10^{-34} kilograms per square meter per second.

A. For an ordinary object—say, a thrown baseball—we could know its position and momentum to 15 or 16 decimal places.

B. For miniscule particles like atoms, photons, and electrons, the numbers are so small that we can never hope for accuracy.

IV. Where does the Heisenberg uncertainty principle come from?

A. A quantum particle moves through space in the form of waves; at any moment, the particle might be found at any point on the wave.

B. Wave intensity gives the probability of finding a particle. The shorter the wave, the more certain we are of position.

C. Momentum is related to wavelength. To determine wavelength accurately, you need an average length of many waves. The longer the wave, the more certain we are of momentum.

D. What we need to be more certain about position is the opposite of what we need to be more certain about momentum, and vice versa.

E. Our knowledge is limited not because of our measurement techniques because the particle itself is indeterminate.

V. There might be other uncertainty principles in nature.

A. A shift in position can be a symmetry: Shifting everything in x does not change the behavior of x, and p is conserved.

B. There is a similar relationship between time and energy. Does this mean there is an uncertainty principle connecting them? Yes! $\Delta t \Delta e > h$. On the quantum level, we cannot know both exactly.

VI. Both of these uncertainty principles have many implications in the quantum world.

A. An electron exists in a standing wave pattern around a nucleus, confined to a small region of space. Thus its momentum is uncertain.

B. In Newtonian physics, a system can be at rest, with zero energy. But in quantum physics, zero energy would require a particle to have an exact position and momentum, which it cannot have.

C. We call this minimum quantum energy zero-point energy, the random thermal vibrations of atoms even near absolute zero.

D. Unlike Newtonian physics, quantum mechanics does not allow for a perfect vacuum. Empty space is really full of an irreducible quantum activity.

E. Quantum theory not only allows but requires the spontaneous appearance of virtual particles in empty space that wink out of existence almost as soon as they appear.

F. A quantum particle can do things that would be impossible for any classical particle, and the implications are amazing.

Questions to Consider:

1. Heisenberg used several different terms to describe his basic idea: uncertainty, indeterminacy, imprecision, latitude, and statistical spread. Remark on the different shades of meaning that these various terms suggest.
2. A stretched wire can vibrate at various frequencies. Can such a wire ever be exactly at rest?

Lecture Nineteen
Quantum Tunneling

Scope:

A Newtonian particle can only pass through a barrier if it has enough kinetic energy to get over the bump in potential energy. But a quantum particle can sometimes sneak through even when its energy would seem to trap it on one side. This effect, called quantum tunneling, explains how trapped nuclear particles can sometimes escape their nuclei, leading to radioactive decay. Tunneling also makes the light cone of a quantum particle slightly "fuzzy."

Outline

I. To understand quantum tunneling, think about a particle moving on a line.

- **A.** Now imagine placing a wall on each side of the particle. In classical physics, the particle bounces back and forth between the walls and eventually stops, trapped.
- **B.** The particle has enough energy to be outside the walls, but it does not have enough energy to get there.
- **C.** In quantum mechanics, the particle behaves like a wave. The wave is most intense between the walls, so the particle is probably there.
- **D.** At the walls, the quantum wave diminishes but does not become zero; it extends slightly into the walls. A very low-intensity wave extends outside the walls.
- **E.** There is thus a tiny probability that the particle will be found outside the walls. This is called the tunneling probability.
- **F.** For a small particle and an atomic-sized barrier, the tunneling probability can be large; for a large object and a strong, thick barrier, the tunneling probability is extremely small.

II. Radioactive decay is a common example of quantum tunneling.

- **A.** In alpha decay, an unstable nucleus emits an alpha particle—2 protons and 2 neutrons—that flies away, carrying energy.

B. The particle's escape was first analyzed by Russian physicist George Gamow.
    1. The nuclear forces are the potential energy barrier, binding the alpha particle to the nucleus.
    2. But particle and nucleus are both positively charged, so electromagnetic repulsion pushes them apart.
    3. The probability of a particle escaping is the probability of the charge repulsion overcoming the nuclear force.

III. Electrical currents are also examples of quantum tunneling.

- **A.** In a piece of solid graphite, electrons are trapped inside atoms. They have high potential energy and no kinetic energy.
- **B.** If you bring the tip of a thin wire very close to the surface, electrons can tunnel from the graphite to the wire, or vice versa. The smaller the gap, the more likely the tunneling.
- **C.** If you move the wire across the graphite and keep track of the number of electrons that tunnel through the gap, you can map out the bumps (smaller gaps) and hollows (larger gaps) in the graphite's surface.
- **D.** This is the basis of the scanning tunneling microscope, a device for creating extremely detailed images of a surface.

IV. Quantum tunneling is related to the uncertainty principle. It is something like the creation and annihilation of a virtual particle in the quantum vacuum.

- **A.** The particle borrows the energy to get beyond the barrier, in effect, from nowhere. After the particle scoots past the barrier, it gives the energy back.
- **B.** If the time and the energy it takes to get past the barrier are small enough, the whole process is hidden by time-energy uncertainty: $\Delta t \Delta e > h$.

V. The most impassable barrier we have seen in this course is the light cone. Can a particle use quantum tunneling to travel faster than light?

- **A.** In relativistic quantum theory, the light cone is still a barrier, and real particles cannot go faster than light. A virtual photon or electron, however, can travel faster than light.

B. We never see virtual particles directly, but we can sometimes see the effects of virtual particles on real particles.

C. The presence of virtual particles makes the light cone slightly fuzzy, its limits less clear.

VI. The fuzziness, or indeterminacy, of the edges of a light cone has an amazing consequence for black holes.

A. Recall that gravity from a black hole bends all light cones inside the event horizon inward, toward the singularity.

B. However, English physicist Stephen Hawking applied quantum physics to particles in warped space-time and showed that black holes participate in the laws of thermodynamics.

C. This means that black holes are not exactly black. They emit Hawking radiation—photons and other particles—because they have a temperature above absolute zero.

D. Hawking radiation is extremely weak—a hundredth of a millionth of a billionth of a watt. Black holes lose energy and shrink, albeit very, very slowly.

E. We can look at Hawking radiation as quantum tunneling, but there is another possibility.

1. Very close to the event horizon, virtual particle-antiparticle pairs appear and disappear in the quantum vacuum.

2. Sometimes one virtual particle is swallowed by the black hole and the other escapes to become a real particle.

3. The escaped particle has positive energy; the swallowed particle has negative energy. In effect, the black hole loses energy.

F. The nature of Hawking radiation is still a bit of a puzzle in physics, called the black hole information paradox.

VII. When a black hole forms from a collapsing star, we seem to lose a lot of information.

A. One current theory is that the information is not lost but scrambled; it returns to us as Hawking radiation.

B. If this is true, then Hawking radiation is a kind of quantum tunneling—tunneling of information.

VIII. It sometimes seems that in quantum physics, just about everything is possible—or at least, if something is impossible, there must be a very important reason.

Questions to Consider:

1. Discuss at least 2 situations in which quantum tunneling makes something previously thought to be physically impossible merely statistically impossible.
2. The term "tunneling" is standard, but it gives the erroneous impression that a quantum particle finds some alternate route (like a wormhole) to get past a barrier. Suggest a better term for this quantum phenomenon.

Lecture Twenty
Whatever Is Not Forbidden Is Compulsory

Scope:

In the world of elementary particles and fundamental forces, the general rule is “anything that can happen, will happen.” However, some reasonable-seeming processes actually are impossible, usually because of a conservation law. We use particle interactions to discuss both exact and approximate conservation laws. In quantum physics, laws that once appeared to be exact may turn out to be approximate, and ordinary matter may turn out to be unstable—in the very, very long run.

Outline

I. “Whatever can happen, eventually must happen” is a principle that particle physicists have long adhered to.

- **A.** Particle physicists observe the behavior of fundamental particles using nuclear reactors, particle accelerators, and cosmic rays.
- **B.** When particles interact—in collisions, in decay, and so forth—lots of things happen in lots of different ways.
- **C.** How do we figure out the rules of physics in a world where absolutely everything seems to happen? By looking for the things that never happen.

II. Let us begin with a quick survey of some ideas in particle physics.

- **A.** There are 4 basic forces in nature.
  1. The strong nuclear, or hadronic, force is the strongest of the 4 and has the shortest range. It binds the particles in a nucleus together.
  2. The electromagnetic force is about 100 times weaker than the strong nuclear force but has a range of whole galaxies. It is the basic force between atoms and molecules.

3. The weak nuclear force is 1 trillion times weaker than the strong nuclear force and has an even shorter range. It is responsible for beta decay.

4. Gravity is by far the weakest force, a trillion trillion times weaker than the weak nuclear force. It has a huge range, however, holding solar systems and galaxies together.

B. On the large scale, gravity is the important force in the universe. On the particle scale, it is negligible.

C. Each type of force has one or more associated particles.

D. Besides the force-carrying particles, there are baryons, the heavy particles found in nuclei; mesons, which include a variety of particles; and leptons, tiny particles such as electrons and neutrinos.

E. Every sort of particle has an antiparticle.

F. Baryons and mesons are made of smaller particles called quarks. Baryons are made of 3 quarks and mesons of 1 quark plus 1 antiquark.

G. Every particle reaction happens because of the strong, weak, or electromagnetic force.

H. Not every kind of particle is affected by every kind of force.

III. When a process is truly impossible, most often this is due to a conservation law.

A. Particles cannot appear out of nowhere or disappear into nowhere because of the conservation of energy.

B. Electrons cannot decay into smaller neutral particles because of conservation of electric charge.

C. Protons do not decay because of conservation of baryon number. This law sounds obscure, but it is one of the most significant facts of nature.

IV. We find new conservation laws by noticing that some reactions are impossible.

  A. If a reaction is possible but rare, we associate it with an approximate conservation law.

  B. Typically, these conservation laws only apply to some of the fundamental forces.

  C. Approximate laws include isospin and parity.

V. A particularly interesting example of an approximate conservation law applies to a baryon called the Λ^0 particle.

  A. Λ^0 is like a heavier cousin of the neutron. It can decay into a proton and a π^- meson, conserving energy, charge, baryon number, and so forth.

  B. All of the particles involved are either baryons or mesons; thus they can all participate in the strong nuclear force.

  C. What is strange about the decay is that, relative to similar processes, it takes an extraordinarily long time to happen.

  D. American physicist Murray Gell-Mann and Japanese physicist Kazuhiko Nishijima proposed an property called strangeness that is conserved by the strong nuclear and the electromagnetic forces but not the weak nuclear force.

  E. Λ^0 has strangeness but decays into unstrange particles. Thus the decay can only take place by the weak nuclear force. A much weaker force means a much slower process and a much longer-lived particle.

VI. We said that the proton is a stable particle—its lifetime is infinite—but how do we know?

  A. According to some modern speculative particle theories, baryon number is not conserved; protons should eventually decay.

  B. A lot of experiments have looked for proton decay but have never seen it.

  C. The current estimate of proton life is at least 1×10^{33} years.

  D. We think Hawking radiation may be an example of baryon number not being conserved—a rare example of gravity affecting particle decay.

Questions to Consider:

1. An electron and a positron can annihilate each other, leaving behind nothing but photons. What conservation law prevents an electron and a proton from annihilating each other in a similar way?
2. To comprehend the meaning of approximate conservation, think of commonplace items that are nearly unchanged over a human lifetime versus items that are created or destroyed much more rapidly. For instance, houses are approximately conserved, while daffodils come and go much more rapidly.

Lecture Twenty-One
Entanglement and Quantum Cloning

Scope:

If a pair of photons is entangled on the quantum level, whenever the polarization of one of the pair is measured, the other is instantly known to have the opposite polarization. Although this seems like instantaneous action at a distance, it cannot be used to send messages faster than light. But if we could build a quantum cloning machine, a device that could perfectly duplicate the polarization of a photon, it could be used to create a telegraph paradox. Luckily, quantum cloning machines are impossible.

Outline

I. Entanglement is a very general feature of the quantum world. Although any type and number of particles may become entangled, the simplest example is an entangled pair of photons.

- **A.** Photons have a special property called polarization, which we can think of as the plane of the light wave's vibration.
- **B.** The wave property of polarization is also a property of the individual photons; each photon is associated with a direction in space.
- **C.** If a vertically polarized photon encounters a vertical polarizer, it can pass through, and if it encounters a horizontal polarizer, it is blocked.
- **D.** If the polarizer has a diagonal direction, we can only predict probabilities that the photon will be transmitted.
- **E.** If the photon passes through the diagonal polarizer, its polarization is changed to that of the polarizer.
- **F.** We cannot directly determine the polarization of a single photon; the best we can do is set our polarizer at some angle and see if the photon goes through or not.
- **G.** We cannot tell for sure what the angle of the polarization was before we did the experiment.

II. A pair of experimentally generated photons move in different directions, but their polarizations will be entangled.

- **A.** Such photons' polarizations are always exactly perpendicular to each other.
- **B.** The so-called common-sense idea about entanglement is that the polarizations are determined the moment the photons are produced. Entanglement is merely prior agreement.
- **C.** Albert Einstein, Nathan Rosen, and Boris Podolsky wrote a paper on quantum entanglement arguing this deterministic view, known as the EPR argument.
- **D.** Quantum mechanics, however, only predicts probabilities, so EPR argues that quantum mechanics must be an incomplete theory of the physical world.

III. The EPR argument was influential but not quite airtight.

- **A.** Irish physicist John Bell was able to turn the EPR argument around by showing that the quantum mechanics of entanglement is actually inconsistent with the consequences of the EPR argument.
- **B.** In the quantum world, either measurement results are truly indeterminate, or the entangled particles must exchange instantaneous messages whenever they are measured.
- **C.** Bell leaned toward the latter view. He said that quantum mechanics was nonlocal.

IV. Does entanglement mean we can send messages faster than light?

- **A.** Not really. A pair of entangled photons can be measured by 2 different observers, but we cannot control which observer receives which polarization—that is, which message.
- **B.** Imagine 2 observers, Alice and Bob.
  1. Alice cannot control the result of her measurement, but she can control which measurement she makes.
  2. Alice can set up her polarizer along the vertical line (situation 1) or a diagonal line (situation 2).
  3. Bob cannot tell the difference between situation 1 and situation 2. He can only make a measurement. Alice's choice does not affect Bob's observation.

C. American physicist Nick Herbert proposed a quantum cloning machine that could copy a single photon exactly.

D. If Bob had such a machine, he could make a hundred copies of his photon and send them through a vertical polarizer.

   1. If Alice measured her photon with a vertical or horizontal polarizer, either 0% or 100% of Bob's photons would come through.
   2. If Alice measured her photon on a diagonal, only 50% of Bob's photons would come through.
   3. Thus the angle of Alice's measurement, not the polarization she measures, can be used as the message.

E. This kind of message is not limited by the speed of light, which means it can create a telegraph paradox.

V. Israeli physicist Asher Peres reviewed Herbert's work and said that we are certain we cannot send information faster than light, so Herbert must be wrong somehow.

   A. A physics journal published Herbert's work, knowing it was incorrect and inviting people to think about why.

   B. Within a few months, Wojciech Zurek, William Wootters, and Dennis Dieks were able to prove the quantum no-cloning theorem mathematically.

   A. Interestingly, the no-cloning theorem has nothing to do with relativity or time travel; it proves that information (such as the polarization of a particle) cannot be perfectly copied.

   B. In some sense, the impossibility of a quantum cloning machine is what safeguards the universe from paradoxes by preserving cause and effect.

Questions to Consider:

1. Is the quantum entanglement between 2 particles a form of information? Why or why not?
2. Suppose Alice and Bob have magic devices that clone quantum particles. Describe in detail how they could use their cloning machines to create a telegraph paradox.

Lecture Twenty-Two
Geometry and Conservation

Scope:

Where do conservation laws come from? How does nature enforce them? We explore this question by examining one particular conservation law, the conservation of electric charge. Electric charge can flow from place to place, but a net electric charge can be neither created nor destroyed. Maxwell's electromagnetic equations and the geometry of space-time imply the conservation of charge by governing how information about charge is communicated to the rest of the universe.

Outline

I. What is the nature of the laws of physics? How do they work? How are they enforced? We explore these questions using conservation of electric charge as our example.

- **A.** Particles can have positive, negative, or zero charge.
- **B.** These particles can move around, be created, or be destroyed, but their charge is always conserved.
- **C.** Imagine a limited region of space-time where we could create or destroy charge. Could we use such a time span to create a net electric charge? Surprisingly, we could not.
- **D.** Charges could be made or destroyed during the period when the laws did not apply, but when the span ends, the charge must end up at zero.
- **E.** If we turn off a conservation law, how is it still enforced? The answer is one of the most remarkable ideas in all of physics.

II. James Clerk Maxwell's electromagnetic equations tell us how electric and magnetic fields are related to charges and each other.

- **A.** A field is what physicists call a region of space-time affected by a particular force.
- **B.** A wind map is a useful analogy. The wind may be fast or slow, headed north or south at any given point, but every point on the map has a particular wind speed and direction.

C. At each point in space-time, the electromagnetic field has a direction (push) and a strength (flux). Keep in mind, however, that nothing is actually flowing through the field.

D. Now, instead of a map, picture a hollow cube.

1. Each side of the cube is a square with a positive side and a negative side. All of the positive sides point outward.
2. The edges of square are positive at one end and negative at the other, in a counterclockwise direction.

E. Flux, in this case, is the flow of wind through a side of the cube. We call this $\vec{F}_W$.

F. We say $\vec{F}_W$ is positive when the wind flows from the negative to the positive side, negative when it flows from the positive to the negative side, and zero when the wind runs parallel to the side.

G. Could $\vec{F}_W$ be positive through all 6 sides at once? Yes, if the wind source is in the center.

H. Push is the wind moving along the edge of a side. $\vec{P}_W$ is positive when it moves from the negative to the positive end of the line, negative when it moves from the positive to the negative end, and zero when it is perpendicular to the line.

I. We have positive net $\vec{P}_W$ when the wind shears counterclockwise around a side.

III. How does this image apply to electromagnetism?

A. The basic laws of electromagnetism are defined by Maxwell's equations, all 4 of which can be explained in terms of the flux and push of the fields.

B. The first equation, Gauss's law (named for Karl Friedrich Gauss) defines charge (q) in terms of the flux of the electrical field: $\vec{F}_E = q$.

C. Returning to our box, if q is positive, field lines flow out of the box. If q is negative, they flow into the box.

D. The second equation, Gauss's law for magnetic fields, is similar: The magnetic flux, $\vec{F}_B$, is always zero.

E. A magnet always has a positive and a negative end. There are no monopoles; nothing is all magnetically positive or negative. The field lines form closed loops or stretch forever.

F. The third and fourth laws deal with the rate of change of x over time ($\dot{x}$).

G. For the third equation, Faraday's law (named for Michael Faraday), we return to our cube.

  1. In this situation, $\vec{F}_B$ is the flux through one side of the cube. This is not necessarily zero, because we are not concerned with the whole cube.

  2. The net electric push around the outside edge of this side of the cube is $\vec{P}_E$.

  3. According to the law, $\vec{P}_E = -\dot{\vec{F}}_B$

H. This is the law that allows a magnet moving rapidly near a wire coil to generate an electric current.

I. In the fourth law, Ampère's law (named for André-Marie Ampère), $\vec{P}_B$ (the net magnetic push around the outside of the square) is equal to I (the electric current through the square in the positive direction).

J. This law is what makes electromagnets work.

K. All of these electromagnetic equations were known before Maxwell came along. His brilliant insight was to realize how they fit together.

IV. Maxwell and his successors derived all sorts of amazing things from the laws.

A. Changing magnetic fields can produce electrical fields.

B. Changing electrical fields can produce magnetic fields.

C. Disturbances in electric and magnetic fields can propagate through empty space as electromagnetic waves.

D. Light is an electromagnetic wave.

V. How does all this prove that we cannot violate the conservation of charge?

A. Imagine a box where we could suspend the conservation of charge for a limited period of time—say, one day.

B. At the start of the day, $q = 0$. No changes cross the walls in either direction all day, so $I = 0$ for the 6 sides of the box.

C. While the laws do not apply inside the box, they are still working outside the box and in the walls of the box.

D. If we apply Ampère's law to each side of the cube, the sum of all the currents of all the sides is zero. No matter what is going on inside the box, the net electric flux through the box does not change—its rate of change is zero.

E. At the end of the day, when the laws go back into effect, Gauss's law for electric fields applies again, so $q = 0$.

F. No matter what happens inside the box during the day, there can be no net charge in the box at the end. The field outside the box still enforces conservation of electric charge.

G. If new charge appears inside the box, it affects the entire electric field, even very far away.

H. The information about the new charge travels as a disturbance, or wave, in the electric and magnetic field.

I. Maxwell's equations say only transverse waves, perpendicular to the field, can travel in the field. But this information requires a longitudinal wave, parallel to the field, to travel.

J. The outside field thus cannot carry the news of the new charge in the box; conservation of charge censors the information, preventing its spread to the rest of the universe.

VI. Do other conservation laws work this way?

A. For energy, conservation is enforced by gravitational fields.

B. Conservation of baryon number is not enforced by any field, but baryon number may not be exactly conserved.

Questions to Consider:

1. Describe what it means for the flux of the wind field through a square to be zero. Describe what it means for the push of the wind field along a line to be negative.

2. Consider empty space in which there are no electric charges or currents. Write down Maxwell's equations in empty space and show that there is a symmetry between electric and magnetic fields in the equations.

Lecture Twenty-Three
Symmetry, Information, and Probability

Scope:

So far, we have used the idea of the impossible as a tool for exploring fundamental ideas in physics. In this lecture, we widen our scope and discuss the course's 3 fundamental themes: the significance of symmetry, the idea of information, and the power of probability.

Outline

I. Symmetry is one of the furthest-reaching mathematical ideas in physics.

- **A.** A symmetry is a transformation of a system such that it is impossible to tell whether or not the transformation has been applied.
- **B.** The first physicists to apply symmetry to physics were the crystallographers, who studied the structure and properties of crystalline solids.
- **C.** The visible shape of a cut crystal reflects its underlying atomic arrangement.
- **D.** Only certain symmetries are possible in 3-dimensional space. The angles of all the sides that meet must add up to 360°.
- **E.** There were 3 crucial developments for the use of symmetry in physics.
  - **1.** In 1894, French physicist Pierre Curie stated Curie's principle: Symmetric causes have symmetric effects.
  - **2.** In 1905, Albert Einstein's special relativity stated that all observers see the same laws of physics regardless of their motion.
  - **3.** In 1915, Emmy Noether proved her amazing theorem connecting symmetries and conservation laws.
- **F.** The most important property of a theory is its symmetry, and the symmetry almost completely determines the theory.

G. Symmetry is so ubiquitous and powerful that it is a lack of symmetry that requires explanation.

H. When underlying laws have more symmetry than the results in a particular instance, we say the symmetry is broken.

I. Broken symmetries may make the underlying laws of our universe appear less symmetric than they actually are.

II. Information is a concept that has come up again and again in this course.

A. Maxwell's demon functions by acquiring and using information, which must then be erased.

B. Chaotic systems are unpredictable because we only have a finite amount of information about them.

C. A time telegraph would lead to a paradox because we could send information into the past.

D. Information is limited by the speed of light, governed by the light cone structure of space-time.

E. The event horizon of a black hole is a surface that traps information—and possibly allows it to tunnel out slowly as Hawking radiation.

F. Entanglement does not allow faster-than-light communication because it is impossible to perfectly copy quantum information.

G. Information is really just a way of talking about cause and effect.

H. The idea of information in modern physics is a relative newcomer, proposed in the late 1940s by Claude Shannon.

I. Quantum physics offers curious and surprising new rules for information, such that we now have quantum information theory.

J. If the last 100 years has been the age of symmetry in physics, the next 100 years may well be the age of information.

III. Probability was not regarded as an important idea in physics until the 19th century.

A. The laws of thermodynamics, originally conceived as perfect laws about definite events, became understood as statistical laws about complicated and chaotic microscopic events.

B. With the rise of quantum theory in the 20th century, probability began to play a more fundamental role in physics.

C. Not even Laplace's demon can know the exact positions and velocities of all the particles in a system, because quantum particles do not even have exact positions and velocities.

D. When we examine the world closely, certainties dissolve, and much of the world's predictability seems mere probability.

E. Perhaps we will find someday that all of the laws of nature are just a matter of odds in a universe governed by chance.

Questions to Consider:

1. How is Curie's principle related to the symmetry breaking? Are the ideas similar or quite different? Discuss.
2. Go back through this guidebook and, for each previous lecture, make a note of which major theme or themes (symmetry, information, probability) play a significant role.

Lecture Twenty-Four
The Future of the Impossible

Scope:

As we discover more about how nature works, the line between the possible and the impossible will have to be redrawn, again and again, in ways we cannot foresee. Yet some enduring insights are possible. Certain principles have survived serious challenges and even whole revolutions in physics. Logical connections can be forged between apparently different concepts—connections that persist whether the concepts are possible or impossible. Until we arrive at a final theory of physics—if such a theory can even exist—the study of the impossible is our best way of thinking about the shape of the undiscovered deep laws of nature.

Outline

I. Our study of the impossible has led us to some quite deep insights into the laws of nature.

- **A.** We have identified the central ideas of symmetry, information, and probability.
- **B.** Our discussion has been based on the best present understanding of the laws of physics, but that understanding is subject to change.
- **C.** Given the possibility of change, is there anything that we can confidently call impossible?

II. In Lecture Two, we heard some wise words from Sir Arthur C. Clarke, the British science fiction writer.

- **A.** Here, we want to discuss his third law: “Any sufficiently advanced technology is indistinguishable from magic.”
- **B.** Is Clarke wrong? Can we distinguish between super-advanced technology, which is based on the fundamental laws of nature, and magic, which is supernatural?
- **C.** In the 18th century, finding the longitude of a ship at sea was a vital puzzle in the science of navigation.

- **D.** Finding latitude, or north-south location, was comparatively easy, based on the angle of the pole star. Finding longitude had no such simple solution.
- **E.** The essential problem was accurately measuring time. Being one minute off could put a ship up to 15 nautical miles out of reckoning.
- **F.** Ships roll and pitch as they travel. Any simple pendulum clock of the day would be knocked off its time.
- **G.** John Harrison—a great English clock maker—worked on the problem for several decades and finally developed a large pocket watch that could keep time to within a few seconds in a sailing voyage across an ocean.
- **H.** As amazing and awe-inspiring as this watch was, it was still obviously a machine, a piece of engineering.
- **I.** Imagine you are John Harrison or one of his contemporaries and someone presents you with a 21st-century GPS unit.
  - **1.** The principles of electricity, of radio communication, and so forth would be totally unfamiliar.
  - **2.** The lack of moving parts would be baffling.
  - **3.** However, after some experiments, you would realize that the GPS follows explicable laws of physics.
- **J.** There were some magical ideas for solving the longitude problem, but even in those days, scientists and engineers understood causality and knew they would not work.
- **K.** New discoveries in physics will lead to unexpected things, but not to things that seem, on examination, like magic.
- **L.** New scientific theories do not really change everything—they always leave a lot of our previous understanding in place.

III. Remember our classification system for the impossible from Lecture One.

- **A.** An absolute impossibility involves a logical or mathematical inconsistency.
- **B.** A physical impossibility, or derived impossibility, violates a law of physics.

C. A statistical impossibility is not impossible but is extremely improbable.

D. Of the 3, a physical impossibility is the weakest, because it depends on the details of the laws, but new discoveries can change the details all the time.

E. Which of the things we have discussed in this course do you think will always remain impossible, even if we discover new laws of physics?

IV. We have examined the impossible as a means to an end. Our real goal has been to understand the unity of physical law—the way the laws of nature work together.

A. Time and again we have found deep and surprising relationships between apparently disparate branches of physics.

B. Time and again we have seen how the central themes of symmetry, information, and probability shape many different branches of physics.

C. As we said at the outset, if our goal is understanding, then there is no tool more practical than the impossible.

Questions to Consider:

1. Why does a hand-held GPS unit require timing signals from at least 4 satellites at once? That is, what is the significance of the number 4 in this case?
2. In your opinion, what piece of modern technology would seem most magical to Galileo? How might he nevertheless begin to discover that it worked according to recognizable physical laws?
3. Construct your own million-dollar list—your list of things that are likely to remain impossible, even if new laws of physics are discovered. Explain why various topics in our course do or do not appear on your list.

Glossary

absolute impossibility: Type of impossibility that involves a logical or mathematical contradiction. This is the strongest and most certain type of impossibility.

absolute zero: The absolute limit of cold, at which all heat energy is removed from a system; equal to about −273°C.

adiabatic: A process that takes place without any exchange of heat with its surroundings, during which entropy remains constant. If a gas undergoes adiabatic expansion, its temperature decreases.

alpha decay: A type of radioactivity in which the nucleus emits an alpha particle (a helium nucleus) composed of 2 protons and 2 neutrons.

Ampère's law: One of Maxwell's field equations for electromagnetism, describing how magnetic fields curl around electric currents and changing electric fields.

anomalous dispersion: An optical phenomenon in certain materials that causes a light pulse to become compressed in time. The center of the pulse may appear to travel faster than the speed of light c, but the leading edge of the pulse does not.

antimatter: A type of matter in which the properties of electric charge, baryon number, and so forth are reversed from ordinary matter. When particles of matter and antimatter collide, they annihilate each other, releasing their energy in a flash of radiation.

arrow of time: The observed asymmetry between future and past directions of time in our universe. This is related to the second law of thermodynamics, which states that entropy tends to increase in the future.

baryons: Heavy elementary particles, including protons and neutrons, that are composed of 3 quarks. Baryons are affected by the strong nuclear force. Baryon number (the net number of baryons minus the number of antibaryons) is apparently conserved.

beta barium borate (BBO): A crystal with nonlinear optical properties, used in the creation of entangled pairs of photons in many laboratory experiments.

beta decay: A kind of radioactivity in which the nucleus emits an electron (or positron) and a neutrino (or antineutrino). Beta decay is an effect of the weak nuclear force.

bit: The elementary unit of information; the information in a single binary message (yes/no, 0/1, etc.). All kinds of information can be expressed in bits.

black hole: A region of space where gravity distorts space-time so much that nothing, not even light, can escape. The outer "surface" of a black hole is called its event horizon.

black hole information paradox: A puzzle of modern black hole physics. Does the information swallowed by a black hole disappear from the universe, or does it reemerge in a distorted way via Hawking radiation?

Bose-Einstein condensate: An exotic low-temperature state of matter in which a suspended cloud of ultracold atoms behaves as a single quantum system.

bosons: Quantum particles that can collect together to form Bose-Einstein condensates.

butterfly effect: A term introduced by Edward Lorenz to describe the extreme sensitivity of a chaotic system like the Earth's atmosphere to the details of its initial conditions. The motion of the wings of a butterfly in Brazil could determine whether or not there are tornadoes in Texas a couple of months hence.

caloric: An old theory that supposed heat to be a kind of invisible fluid. Warm objects had more caloric, while cold objects had less; heat flow was simply the transfer of caloric.

Casimir effect: A tiny attractive force between parallel metal plates due to their effect on the quantum vacuum energy in their vicinity.

causal loop: A closed chain of cause and effect, in which A causes B, B causes C, but then C causes A. Causal loops open the door to paradoxes like those of time travel (i.e., the grandfather paradox and the telegraph paradox).

Chandrasekhar limit: The upper limit to the possible mass of a white dwarf star, about 1.4 times the mass of our Sun. A star larger than this limit must become a neutron star or a black hole.

chaos: A type of dynamics in which the future state of a system is extremely sensitive to its initial conditions. Although the general characteristics of chaotic systems can be determined, long-term detailed predictions of their behavior is impossible.

charge conjugation: A transformation in which particles of matter are replaced by those of antimatter and vice versa. Although charge conjugation is an approximate symmetry of nature, it is not exact because of the weak nuclear force.

Cherenkov radiation: The radiation emitted by a particle traveling faster than the speed of light in a transparent medium like water or glass. The particle, however, does not travel faster than the vacuum speed of light c.

chronology protection conjecture: A proposal by Stephen Hawking that some as-yet-unknown general principle of nature forbids the existence of causal loops, protecting the universe from paradoxes.

Clarke's laws: Three observations by science fiction writer Arthur C. Clarke about the limits of our ability to predict future developments in science and technology.

classical physics: Essentially, the physics developed before 1900, encompassing Newtonian mechanics, thermodynamics, and electromagnetism. The revolutions of relativity and quantum theory go beyond classical physics.

closed timelike curve: A path in space-time that is both a closed loop and a possible particle trajectory. Space-times with closed timelike curves admit causal loops.

congruent: Geometric figures with equal corresponding lengths and angles.

CPT: A transformation that combines charge conjugation, parity, and time reversal. According to a mathematical theorem of quantum theory, CPT is an exact symmetry of nature.

crystallography: The study of the structure and properties of crystalline solids.

Curie's principle: Introduced by Pierre Curie, this principle states that symmetric causes have symmetric effects.

deep time: The idea, first understood by geologists and paleontologists, that the present Earth is the result of processes acting over immense spans of time—hundreds of millions or billions of years.

derived impossibility: Type of impossibility that contradicts an accepted assumption about the world. For example, a physical impossibility is a derived impossibility from the accepted laws of physics.

electromagnetic force: One of the 4 basic forces of nature. The electromagnetic force is long ranged, relatively strong, and affects all particles with electric charge.

electromagnetic miracle: An imaginary exception to the laws governing electric and magnetic fields, extending over some region of space and time.

energy: One of the most fundamental quantities of nature. Energy has different forms, including kinetic energy, potential energy, heat, nuclear energy, and so on. Energy is conserved—that is, it cannot be either created or destroyed.

entanglement: A property of quantum physics in which separated quantum particles can behave in correlated ways.

entropy: A quantity introduced by Rudolph Clausius to measure the unavailability of energy to do useful work. Later, it was recognized that entropy is a measure of the information we lack about the microscopic details of a system.

EPR: Albert Einstein, Boris Podolsky, and Nathan Rosen, who authored a famous early paper about quantum entanglement. EPR believed that entanglement showed quantum theory to be incomplete; later on, John Bell's work showed their argument to be fatally flawed.

event: A point in space-time, designated by its location in both space and time.

event horizon: The mathematical boundary of a black hole. Events within the event horizon can never be seen by any observer outside the event horizon.

exchange symmetry: A symmetry of nature in which identical bosons or fermions are exchanged. Since all electrons (for instance) are exactly identical, a swap of 2 electrons would be impossible to detect.

exotic matter: An imaginary type of matter with properties unlike any known substance, especially matter with an overall negative energy density.

Faraday's law: One of Maxwell's field equations for electromagnetism, describing how electric fields curl around changing magnetic fields.

fermions: Quantum particles obeying the Pauli exclusion principle, which states that no 2 fermions can occupy the same quantum state.

field: A physical effect (like the electric, magnetic, or gravitational field) that extends throughout space.

flux: The net amount of a field that "flows" through a surface. The concept is directly related to flow for the wind field but can be extended by analogy to electric and magnetic fields.

Gauss's law for electric fields: One of Maxwell's field equations for electromagnetism, describing how electric fields are produced by electric charges.

Gauss's law for magnetic fields: One of Maxwell's field equations for electromagnetism, describing how there are no isolated charges for magnetic fields.

global positioning system (GPS): A system of satellites orbiting Earth that allow special receiving units to precisely determine their position and time.

grand unified theories: Speculative extensions of known particle physics that unite the strong, electromagnetic, and weak forces. In grand unified theories, baryons are sometimes thought to be slightly unstable.

grandfather paradox: A paradoxical situation in which a time traveler goes back to the past and kills his grandfather, preventing his own birth. Despite efforts to resolve this paradox, the possibility of such an action is usually taken as evidence that time travel is impossible.

gravitational force: One of the 4 basic forces of nature. Although it is a long-range force, it is by far the weakest and is usually ignored in particle physics. In relativity, gravity is described by the curvature of space-time geometry.

group theory: The general mathematical theory of symmetry, first developed in the 19th century.

hadrons: Particles that are affected by the strong nuclear (or hadronic) force, including both baryons and mesons.

Hawking radiation: Weak emission of photons and other particles from black holes due to quantum effects near the event horizon. The black hole behaves as if it had a (very low) temperature, called the Hawking temperature.

heat engine: A machine for turning heat energy into work. As Sadi Carnot realized, such an engine can only operate between a temperature difference.

Heisenberg uncertainty principle: A principle discovered by Werner Heisenberg stating that a quantum particle cannot have both a definite position in space and a definite momentum at the same time. The product of the uncertainties in these 2 quantities must always be at least as big as Planck's constant.

hydrogen fusion: The nuclear reaction that produces energy in the cores of the Sun and other stars. By a sequence of reactions, 4 hydrogen atoms are converted into 1 helium atom, releasing 0.7% of the rest of the mass as energy.

indeterminism: The feature of quantum theory by which the future behavior of a system is not completely determined by its present state. On the contrary, quantum theory only predicts probabilities for various possible outcomes of an experiment.

isospin: A particle property that represents the "protonness" and "neutronness" of nuclear particles. Isospin is approximately conserved, but in some reactions (like beta decay) it can change.

isothermal: A process that takes place at a constant temperature. A gas that undergoes isothermal expansion will have to absorb heat from its surroundings.

jiffy: An extremely short unit of time, defined as the time required for light to travel across an atomic nucleus (about 3×10^{-24} seconds).

joule: The basic unit of measurement of energy, named after physicist James Joule. An orange tossed upward is given about 1 joule of kinetic energy.

kinetic energy: The energy an object has due to its motion through space. This is proportional to the object's mass and the square of its speed.

Laplace's demon: An imaginary being discussed by Pierre-Simon Laplace. The demon possesses exact knowledge of all of the positions and velocities of all the particles in the universe. By applying Newton's laws of motion, the demon could, in principle, predict the exact future history of the universe.

latitude: North-south position on Earth's surface. Determining longitude is a relatively easy navigational task, requiring only the measurement of angles.

Lense-Thirring effect: An effect of relativity in which a rotating mass can slightly "drag along" a nearby observer's sense of rotation.

leptons: A family of elementary particles including the relatively low-mass electrons and neutrinos.

light cone: The cone-shaped area of space-time describing how a spherical pulse of light spreads out from an event. The light cone marks the boundary between those parts of space-time that can be influenced by an event and those that cannot. Thus light cones map out the causal structure of space-time.

longitude: East-west position on Earth's surface. Determining longitude is a relatively difficult navigational task, since it requires a very exact determination of time. The British Parliament established a large prize in the 18^{th} century for the development of a practical method for finding longitude at sea.

Mach's principle: An idea proposed by Ernst Mach that an observer's sense of rotation (due to local inertial effects) is related to the overall distribution of mass in the cosmos. Thus an observer who feels no inertial tendency for his arms to fly outward will also observe no net turning of the distant galaxies.

many-worlds interpretation: An interpretational scheme for quantum theory in which all possible outcomes of an experiment actually occur in difference branches of the universe.

Maxwell's demon: An imaginary being discussed by James Clerk Maxwell. The demon observes the motions of gas molecules in 2 containers and operates a door between them. The demon appears to violate the second law of thermodynamics by acquiring and using information, but a more detailed analysis (including the process of information erasure) shows that it does not.

Maxwell's equations: The 4 fundamental equations that govern the behavior of electric and magnetic fields, first put into complete form by James Clerk Maxwell.

mesons: A family of elementary particles of intermediate mass. Mesons are affected by the strong nuclear force and are composed of a combination of one quark and one antiquark.

momentum: In Newtonian physics, the mass times the velocity of a moving particle.

neutrino: A nearly invisible particle produced in beta decay, first posited by Wolfgang Pauli and Enrico Fermi but not directly detected for 25 years.

neutron star: An extremely dense stellar remnant composed almost entirely of neutrons. A neutron star is the end point of the evolution of a star larger than the Chandrasekhar limit but not large enough to collapse into a black hole.

Noether's theorem: The theorem proposed by Emmy Noether that establishes a connection between symmetries and conservation laws.

Novikov self-consistency principle: A hypothesis of Igor Novikov that the laws of the universe enforce consistency even in the presence of causal loops, making time paradoxes impossible.

parity: A transformation that exchanges left and right in a system, like a reflection in a mirror. Parity is an approximate symmetry of nature, but experiments on beta decay show that it is not exact.

perpetual motion machine: An impossible machine that can run forever and do useful work. A perpetual motion machine of the first kind creates more energy than it consumes, in violation the first law of thermodynamics. A perpetual motion machine of the second kind extracts heat and turns it all into work, in violation of the second law of thermodynamics.

photoelectric effect: A phenomenon in which light incident on a metal surface causes electrons to be ejected from the surface. The analysis of the photoelectric effect by Albert Einstein was an early success of quantum theory.

physical impossibility: Impossibility due to violation of accepted physical laws. Thus physical impossibility is a type of derived impossibility.

Planck's constant: Denoted *h*, this extremely small quantity (numerically equal to 6.63×10^{-34} joule-seconds) governs the scale of quantum effects.

polarization: A direction associated with a light wave, representing the plane of oscillation of the electric field. Light may be polarized in any direction perpendicular to its plane of motion. Polarization is also a property of the photons composing the light beam.

positivism: A philosophical view that asserts that human knowledge is only based on the senses and that only statements that can be tested in this way are allowed as scientific statements.

positrons: The antiparticles of electrons, having the same mass but possessing positive electric charge.

potential energy: Energy due to the position of a particle. A projectile has its greatest gravitational potential energy at the top of its trajectory.

powder of sympathy: A fanciful suggestion for solving the problem of longitude, based on the alleged properties of a special powder. Manipulating a discarded bandage (treated by the powder) was supposed to produce an instantaneous reaction in an injured animal, even thousands of miles away. It did not really work.

proof by contradiction: A technique of mathematical proof favored by Euclid. In a proof by contradiction, an impossible situation is hypothesized and shown to lead to a logical contradiction. This is also known as reductio ad absurdum.

push: The net movement of a field along a line or around a closed path. The concept is directly related to motion for the wind field but can be extended by analogy to electric and magnetic fields.

quantum cloning machine: An imaginary machine that can exactly duplicate a quantum particle such as a photon.

quantum no-cloning theorem: The principle discovered by William Wootters, Wojciech Zurek, and Dennis Dieks that a quantum cloning machine is impossible under the laws of quantum theory.

quantum theory: The revolutionary new theory of the physics of the microscopic world developed between 1900 and 1930. The term is nearly synonymous to quantum physics and quantum mechanics. Important features of quantum theory include wave-particle duality, indeterminism, and entanglement.

quantum tunneling: The surprising phenomenon by which a quantum particle can sometimes pass through a potential energy barrier that would (under classical physics) ordinarily be expected to block it.

quarks: The elementary constituents of baryons and mesons.

radioactivity: The decay of unstable atomic nuclei over time. In radioactivity, various types of particles may be emitted, and the original nucleus is transformed into a different nucleus of lower energy.

reductio ad absurdum: "Reduction to absurdity," another term for proof by contradiction.

relativity of simultaneity: The statement that events that happen at the same time in the frame of reference of one observer might not happen at the same time in the frame of reference of a different observer.

scanning tunneling microscope: A device that uses quantum tunneling to obtain images of surfaces at extreme magnification. They can routinely image individual atoms in a surface.

sensitive dependence on initial conditions: The characteristic property of dynamical chaos, also known as the butterfly effect. Tiny changes in the initial state of a system can quickly lead to very different future states.

singularity: The mathematical cusp in the space-time at the center of a black hole, in which (according to relativity) the mass of the collapsed star is compressed to a single point.

solar neutrino problem: The strange deficit in the number of neutrinos emitted by the Sun, based on our understanding of nuclear reactions. This problem was resolved by the discovery that neutrinos oscillate between different types as they travel.

space-time: The 4-dimensional world, the true arena of physics, introduced by Hermann Minkowski. Space-time includes all points in space at all moments of time.

spectroscopy: The analysis of the makeup and physical state of matter based on the light that it emits. Spectroscopy allows us to determine the composition of distant stars, even though we are not able to travel to them.

spiracles: Small pore-like passages in the outer surface of an insect, allowing it to take in oxygen from the atmosphere. This system of respiration works for small animals, but larger animals require complex lungs.

square-cube law: The mathematical relation between area and volume, stating that larger objects have proportionally smaller areas relative to their volumes. Galileo Galilei noted this law and related it to the strength of structures and the body designs of animals of various sizes.

statistical impossibility: Type of effective impossibility that comes from extremely low probability—for instance, the likelihood of obtaining 10,000 heads in a row by flipping a fair coin. Though not strictly impossible, such an event is so unlikely that it can be regarded as impossible for all practical purposes.

strangeness: An approximately conserved property of elementary particles. Because strangeness can only be changed by the weak nuclear force, some particles can exist trillions of times longer than expected.

strong nuclear force: Also known as the hadronic force, the strongest of the 4 basic forces of nature. The strong nuclear force has a very short range, only a fraction of the diameter of an atomic nucleus.

superconductor: A material that has zero electrical resistance at temperatures near absolute zero.

superfluid: A liquid like Helium II that has zero viscosity (resistance to flow) and is a perfect heat conductor at temperatures near absolute zero.

symmetry: A transformation that leaves a system unchanged. A geometrical shape may be symmetric if some transformation (e.g., reflection) leads to a congruent shape. Symmetry is one of the basic characteristics of the laws of physics.

symmetry breaking: A situation in which the symmetry of the underlying laws may not be reflected in a particular symmetry. Thus right-handed and left-handed DNA molecules have identical chemical properties, but because of evolutionary history, only right-handed DNA is used by Earth organisms.

telegraph paradox: A time paradox involving sending information into the past. The message sent from the future is chosen to be different from that received in the past. This is equivalent to the more famous (but more violent) grandfather paradox.

thermophiles: Bacteria that thrive at extremely high temperatures, even above 100°C.

three-body problem: The problem of determining the future motion of 3 bodies that orbit each other under their mutual gravitation. Even though this sounds like a simple system, it is chaotic, so long-term prediction is impossible.

time dilation: An effect of relativity by which clocks moving close to the speed of light run slowly.

time machine: An impossible machine introduced by the science fiction writer H. G. Wells that enables its user to travel into the past. Time travel into the future is not impossible—in fact, we are all doing it all the time.

time telegraph: A cousin of the time machine that permits messages to be transmitted into the past.

unbalanced wheel: One of the classic designs of a perpetual motion machine. Moving weights apparently cause the wheel to rotate forever on its own, doing useful work. Like other perpetual motion machines, unbalanced wheels do not operate as advertised.

vector: A quantity (like wind velocity or electric or magnetic fields) that has both magnitude and direction.

virtual particles: Particles that emerge and disappear from the quantum vacuum, but whose existence is hidden "underneath" the uncertainty principle. Virtual particles are never directly observed, but their effects can be significant.

wavelength: The distance between successive crests of a periodic wave.

wave-particle duality: The quantum principle by which light and matter exhibit both wave and particle properties. Thus light propagates through space as if it were a continuous wave phenomenon but exchanges energy with matter as if it were a stream of discrete photons.

weak nuclear force: One of the 4 basic forces of nature. The weak force, which is responsible for beta decay, has a very short range. It is also the only basic force that is not symmetric under parity—that is, the weak force is the only force that can tell left from right.

white dwarf star: A dense stellar remnant that is the endpoint of the evolution of a star less massive than the Chandrasekhar limit. A white dwarf star with the same mass as the Sun would be about the diameter of Earth.

work: A force acting through a distance; this measures how much the force on an object changes its energy.

world line: The path of a body through space-time, including all the spatial locations of the body at all times. World lines are generally vertical—that is, roughly aligned with the time axis in a space-time diagram; their tilt and curvature represent the velocity and acceleration of the particle.

wormhole: A shortcut through space-time connecting 2 distant regions. In relativity, wormholes collapse into black holes too quickly to be traversed unless they contain exotic matter (i.e., matter with negative energy).

zero-point energy: The energy always present in a quantum system, even in its lowest energy state, due to the uncertainty principle.

Biographical Notes

Alcubierre, Miguel (b. 1964): Mexican physicist and expert on space-time geometry. Alcubierre is best known for his unusual solutions to Einstein's equations of general relativity, most notably his warp drive space-time. In this geometry, an object is enclosed in a bubble that travels through space faster than light, although the object itself is at rest within the bubble. This space-time requires the existence of an unknown type of matter with negative energy density. Alcubierre is now a professor at the National Autonomous University of Mexico, where he works on computational solutions to Einstein's equations.

Ampère, André-Marie (1775–1836): French physicist who made important contributions to the theory of electromagnetism. Ampère never went to school but was educated at home under the supervision of his father, a prosperous businessman and minor government official. Early on, Ampère showed considerable mathematical talent. His father was sent to the guillotine during the French Revolution, a disaster that devastated his son. Ampère became a teacher of mathematics and published early work on probability theory and the calculus of variations, joining the faculty at the École Polytechnique in 1809. In addition to his mathematical work, he did research in chemistry, optics, philosophy, and electromagnetism. Hearing of the work of Dutch physicist Hans Christian Ørsted, Ampère took only a matter of days to figure out the basic law governing the magnetic effect of electric current. In 1826, he joined the faculty at the Collège de France, an appointment he held till his death.

Bell, John (1928–1990): British physicist. Although he was trained and worked as a particle physicist, spending most of his career at the European particle physics lab CERN in Geneva, he found time to think deeply about the foundations of quantum theory. He did a brilliant and fateful reanalysis of the 1935 argument of Einstein, Podolsky, and Rosen. This led him in 1964 to prove his remarkable theorem, stating that no mechanism of local hidden variables could ever reproduce the statistical correlations between entangled quantum systems. The exact conclusion to be drawn from this has been a subject of debate ever since; Bell's own view seems to have been that the concept of locality could not be maintained in quantum theory.

Bohr, Niels (1885–1962): Danish physicist and one of the fathers of quantum mechanics. After receiving his doctorate in Denmark, Bohr spent several years in England, where he worked for Ernest Rutherford. Bohr applied quantum ideas to atomic structure, explaining atomic spectra by the discrete orbits allowed for the electron in the atom. After returning to Denmark, he established the Institute for Theoretical Physics in Copenhagen. This became the center for work on the new quantum physics; young physicists from all over Europe and America studied and worked there. While others created the mathematical theory of quantum mechanics, Bohr carefully laid its conceptual foundations. His fierce but friendly debate with Albert Einstein about the nature and meaning of quantum physics explored many of the puzzles of the quantum realm. In 1939, on the eve of World War II, Bohr and John Wheeler developed the liquid drop model of the atomic nucleus, the basis for the theory of nuclear fission. Bohr spent the first part of the war in occupied Copenhagen, but then, forced to make a daring escape because of his Jewish ancestry, he participated in the U.S. Manhattan Project to develop the nuclear bomb. After the war, he returned to Denmark. Bohr's ideas and personality were tremendously influential among theoretical physicists. He was always ready to consider radical new thinking; to one colleague, he said, "Your theory is crazy, but it's not crazy enough to be true."

Bose, Satyendra (1894–1974): Indian physicist most notable for the discovery of the statistical laws governing one type of identical particle in 1922. Bose made his discovery in the middle of a lecture at the University of Dakha, in which he was attempting to demonstrate that classical statistical physics could not explain Planck's blackbody radiation law. During the lecture, he made a "mistake" that unexpectedly led to the correct answer. Bose soon realized that he had stumbled on a new insight into the quantum world. Bose sent his paper to Einstein, who recognized it as an important contribution, saw to its publication, and worked to develop its ideas further. Bose became an important figure in the growth of science in India.

Carnot, Sadi (1796–1832): French engineer and physicist whose penetrating analysis of the steam engine led the way to the second law of thermodynamics. Born to a political family (his father was Napoleon's minister of war), Carnot joined the French army and served as an engineer during the Napoleonic wars. During the relative peace of the 1820s, Carnot was able to indulge in his passion for science. His interest in the steam

engine was partly practical, since it was unknown how efficiently one could operate. To answer such a question required a general theory of steam engines, which Carnot set out to discover. His small treatise on the subject, *Reflections on the Motive Power of Fire*, is one of the great classics of science. Carnot himself returned to active service during the Revolutions of 1830 and died 2 years later. The importance of his contribution was only realized by later scientists.

Casimir, Hendrik (1909–2000): Dutch physicist who contributed to both low-temperature physics and quantum electrodynamics. Casimir studied with the great Paul Ehrenfest, then worked with Niels Bohr in Copenhagen and Wolfgang Pauli in Zurich. Although he was an industrial scientist, directing the Philips Research Laboratories in the Netherlands, he made numerous contributions to pure research. In 1948, he predicted the phenomenon that later bore his name (the Casimir effect) in which 2 metal plates are attracted to each other due to their modification of the quantum vacuum.

Chandrasekhar, Subrahmanyan (1910–1995): Indian American astrophysicist who made many discoveries about the lives and deaths of stars. Known as Chandra throughout his life, he was born and received his initial education in physics in India. His uncle was physicist C. V. Raman, who won the Nobel Prize for Physics in 1930. In the same year, Chandra left India to study at the University of Cambridge. By that time, he had already started the work that established an upper limit to the mass of white dwarf stars, implying the existence of neutron stars. In 1937, he accepted a faculty position at the University of Chicago, where he remained for the rest of his distinguished career. It is safe to say that no single person has contributed more to our detailed understanding of stellar evolution. Chandra was also the editor of *The Astrophysical Journal* for almost 2 decades and the writer of numerous thoughtful essays and lectures on Isaac Newton.

Clarke, Arthur C. (1917–2008): British science fiction writer and astronautics expert. In 1945, Clarke was the first to propose using satellites in geosynchronous (24-hour) orbits as communication relays. He gained his greatest fame as a writer of science fiction, writing such classics as *Childhood's End*, *2001: A Space Odyssey* (on the film of which he collaborated with director Stanley Kubrick), and *Rendezvous with Rama*. Clarke's fiction was notable for well-informed speculations about future technology and profound mediations on the place of humanity in the

universe. Besides his enthusiasm for space travel, he also had a lifelong passion for scuba diving and deep-sea exploration, about which he wrote several books.

Clausius, Rudolf (1822–1888): German physicist who formulated some of the basic principles of thermodynamics. After an education in Berlin and Halle, Clausius spent his life as a professor in several German-speaking universities in Berlin, Zurich, Wurzburg, and Bonn. His most famous contributions are his formulations of the first and second laws of thermodynamics in 1850 and his introduction of the concept of entropy in 1865. He led an ambulance corps in the Franco-Prussian War of 1870. He was wounded and later received the Iron Cross. After his wife died in 1875, leaving him to raise 6 children on his own, he had less time for research. He nevertheless remained a dedicated scholar and teacher; according to his brother, "even on his last sickbed he held an examination."

Curie, Pierre (1859–1906): French physicist remembered today as the husband of Marie, but in fact a remarkable scientist in his own right. Curie's father was a Parisian doctor, but it was clear from early on that the son's interests were more theoretical. As he rose through the ranks of French academia, Curie first studied crystallography and then magnetic phenomena, making essential contributions to both. His work was notable for its deep mathematical sophistication as well as its careful experimental basis. In 1895, Curie married Marie Sklodowska, a brilliant Polish graduate student. They began a decade of joint work, becoming the most famous husband-and-wife team in the history of science. Their studies of radioactivity, including the isolation of radium and polonium, earned them the Nobel Prize for Physics in 1903. Three years later, Curie was run over by a wagon and was killed instantly, leaving his wife to carry on their work alone. (She won a second Nobel Prize in 1911.)

Davis, Raymond, Jr. (1914–2006): American scientist whose solar neutrino experiment posed one of the thorniest puzzles of contemporary physics. Davis, a chemist, spent World War II working on chemical warfare out in the deserts of the American southwest. After the war, he joined Brookhaven National Laboratory, where he began work on nuclear physics. Early attempts by Davis to detect neutrinos in the Brookhaven reactor failed but inspired his lifelong quest to understand these elusive particles. His neutrino detector, built in an abandoned gold mine in South Dakota, only detected about a third of the expected number of neutrinos from the Sun. This solar

neutrino problem was resolved when it was shown that neutrinos oscillate among 3 varieties as they travel through space; Davis's detector could only detect one neutrino type.

de Broglie, Louis (1892–1987): French physicist who, in one of the most influential doctoral dissertations in history, proposed that electrons and other quantum particles must have wave characteristics. De Broglie's work closed the circle of quantum ideas and in short order became the basis for the wave mechanics of Schrödinger. De Broglie, who was a member of the French nobility, became one of the most eminent men in European science after World War II.

Deutsch, David (b. 1953): Israeli English physicist and one of the most creative and eccentric thinkers in contemporary quantum theory. Deutsch was one of the originators of the idea of a quantum computer, motivated by his interest in the many-worlds interpretation of quantum mechanics. An intelligent quantum computer, he reasoned, could be a type of observer that was aware of the branching of the universe's quantum state. Deutsch has made many contributions to the theory of quantum computing. He has also applied his combination of rigorous mathematics and powerful imagination to other even more speculative topics, such as the quantum physics of time machines. Deutsch is affiliated with, but not a faculty member at, Oxford University. He is seldom seen outside of Oxford, but his ideas are closely followed by quantum physicists worldwide.

Dirac, Paul (1902–1984): English physicist who contributed deeply to the mathematical tools of quantum theory. As a graduate student at the University of Cambridge in the 1920s, Dirac seized on the new theories of Heisenberg and Schrödinger, demonstrating their mathematical equivalence. In 1928, he proposed a new form of quantum theory compatible with Einstein's special theory of relativity, including a relativistic version of the Schrödinger equation later known as the Dirac equation. Consideration of this equation led Dirac to predict the existence of antiparticles. These were discovered only a few years later in studies of cosmic rays. Dirac laid the groundwork for the quantum theory of fields (including quantum electrodynamics) and was one of the first to analyze the statistical properties of identical particles—to mention only 2 of his remarkable contributions. For over 30 years, he held Isaac Newton's old post as Lucasian Professor of Mathematics at Cambridge. Dirac's scientific work was guided by a passionate belief in the mathematical elegance of nature. He is buried in

Florida, where he spent the last decade of his life, but his monument in Westminster Abbey is just a few steps from Newton's tomb.

Einstein, Albert (1879–1955): German physicist, later an American citizen, whose epoch-making contributions to physics during the early 20th century turned him into a public icon of a scientific genius. His fame was entirely deserved. In a series of brilliant papers in 1905, the young Einstein (then working as a patent clerk in Switzerland) made fundamental discoveries in statistical mechanics, established the special theory of relativity, and used Planck's quantum hypothesis to explain the photoelectric effect. More contributions followed, including his quantum explanation of the heat capacities of solids, many papers on the interaction of light with matter, and the statistical behavior of identical particles. Einstein's 1915 discovery of the general theory of relativity, which explains gravitation as the curvature of space and time, was as astonishing as it was profound. The confirmation of this theory came a few years later, just after World War I, when the deflection of starlight by the Sun's gravity was precisely measured. This was the event that catapulted Einstein to international celebrity. Although Einstein was one of the pioneers of quantum theory, he later became its sharpest critic. His debates with Bohr at the 1927 and 1930 Solvay conferences were decisive turning points in the history of the subject. Einstein, a Jew, left Europe for America in 1932 and never returned. In 1935, Einstein, Boris Podolsky, and Nathan Rosen argued that the phenomenon of quantum entanglement proved that quantum theory was an incomplete description of reality. (This argument, and Bohr's subtle reply, led John Bell to his remarkable work 3 decades later.) In later years, Einstein worked unsuccessfully to combine the known laws of physics into a unified field theory. Einstein was never fully reconciled with quantum physics, never quite accepting that "God [plays] dice with the universe." In all of his scientific work, he was guided by the maxim, "The Lord God is subtle, but He is not malicious."

Euclid (b. c. 300 B.C.): Greek geometer whose magnificent treatise *Elements* on geometry and arithmetic became a standard mathematics textbook for over 2000 years. We know next to nothing about Euclid's life—indeed, some scholars have even suggested that "Euclid" is just a collective pseudonym for an entire school of geometers. However, it is generally believed that Euclid lived and worked in the Greek city of Alexandria in Egypt. Euclid set the modern mathematical standard of establishing conclusions by rigorous logical proof based on explicit axioms.

His penchant for proof by contradiction nominates him as our patron saint of absolute impossibility.

Faraday, Michael (1791–1867): English physicist whose discoveries in electromagnetism laid the basis for new theories and practical developments. Faraday was the son of a blacksmith and had neither much formal education nor a high social position. Nevertheless, his eagerness and talent landed him a job as an assistant to chemist Humphrey Davy, which proved the doorway to a distinguished scientific career. Faraday was a great experimental scientist rather than a mathematician, but his intuitive way of picturing fields by field lines inspired later theoretical work by James Clerk Maxwell and others. Faraday is most remembered for his discovery of electromagnetic induction. He was also well known during his lifetime as a popular lecturer at the Royal Institution in London. After one of his electrical demonstrations, a lady in the audience asked him of what use electricity was. Faraday is said to have answered, “Madam, will you tell me the use of a newborn child?” (The story may be apocryphal; a similar story is told about Benjamin Franklin.)

Fermi, Enrico (1901–1954): Italian physicist, later an American citizen, who made brilliant contributions to both theoretical and experimental physics. In 1926, while still in Rome, Fermi helped to develop the statistical theory of identical particles such as electrons that obey the Pauli exclusion principle. Later, he became even more famous for his remarkable experiments on neutron-induced nuclear transformation, for which he won the Nobel Prize and in which he narrowly missed discovering nuclear fission. His groundbreaking theory of beta decay included Pauli’s undiscovered ghost particle, which Fermi christened the neutrino. After leaving Fascist Italy and emigrating to the United States, Fermi worked on the Manhattan Project. His experimental reactor achieved the first sustained nuclear chain reaction in 1942.

Galilei, Galileo (1564–1642): Italian physicist and astronomer and one of the fathers of modern science. Despite his father’s wish that he become a doctor, young Galileo studied mathematics instead at the University of Pisa, eventually becoming a mathematics teacher. After hearing of the Dutch invention of the telescope, Galileo built his own and was one of the first to use it to examine the heavens. His astounding discoveries, explained in many popular treatises beginning with *The Starry Messenger* (1610), tended to support the Copernican theory that Earth was a planet

orbiting the Sun. Galileo's advocacy for Copernicus led to conflict with ecclesiastical authorities of the day. With the election of Pope Urban VIII, Galileo believed he had an ally in the papacy and so wrote his greatest work, *Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican* (1630). Although this book is framed as an even-handed discussion in which both Copernican and older Ptolemaic ideas are presented, Galileo's own sympathies and conclusions are obvious. Church authorities were not amused. Forced to recant in a trial before the Inquisition, Galileo spent the rest of his life under house arrest. He nevertheless produced one more groundbreaking book, *Dialogue Concerning Two New Sciences* (1638), laying the foundations on which Newton later built his theory of mechanics. Galileo combined keen mathematical insight with a strong practical bent, a razor-sharp intellect with an even sharper polemical wit, and a sincere religious faith with an abiding confidence in human reason. His discoveries launched the scientific revolution, and his imprisonment was one of the great tragedies of intellectual history.

Gamow, George (1904–1968): Russian American physicist known for his contributions to cosmology and quantum physics, as well as for his sense of humor. Gamow was born in Russia and studied cosmology with Aleksandr Friedmann before emigrating to the West. At Niels Bohr's institute in Copenhagen, Gamow used quantum tunneling to explain some alpha decay, a type of radioactivity. Coming to the United States in 1934, Gamow worked on cosmology and the big bang theory. A typical example of his exuberant sense of fun is a paper that he wrote with Ralph Alpher about the formation of the chemical elements in the big bang. Gamow insisted on recruiting Cornell physicist Hans Bethe as a third coauthor, resulting in the famous Alpher-Bethe-Gamow paper. (Bethe claimed to have made no contribution beyond his name.) Later on, Gamow wrote excellent popular books on physics illustrated with his own hilarious cartoons.

Gauss, Karl Friedrich (1777–1855): German mathematician recognized as one of the great mathematical minds of all time, who also made many contributions to physics. From his earliest years, Gauss was a prodigy. He had a rare combination of gifts, being both a mathematical genius and a lightning calculator. Gauss spent most of his career as a professor at the University of Göttingen. His discoveries in pure mathematics—in number theory, algebra, analysis, probability, and non-Euclidean geometry—are numerous and important. For example, he proved the fundamental theorem

of algebra (that every polynomial has at least one complex root.) In his later career, he focused on applied mathematics. Gauss created new methods for determining the orbits of objects in our solar system, supervised a new accurate survey of the kingdom of Hanover, and developed mathematical methods for describing electric and magnetic fields.

Gell-Mann, Murray (b. 1929): American particle physicist known for his wide interests and witty wordplay. In the 1950s, first at the University of Chicago and then at Caltech, Gell-Mann brought order to the growing menagerie of elementary particles. His concept of strangeness explained why certain particles were anomalously long-lived. His eightfold way mapped out the properties of elementary particles and predicted the existence of new types, much like Mendeleev's periodic table of the elements in the 19th century. Gell-Mann was also one of the originators (and the namer) of the quark model, which revealed the inner structure of protons, neutrons, and mesons. His mathematical elegance and humorous terminology have had a profound impact on theoretical physics. Gell-Mann later became a champion of string theory and has made many contributions to the study of complex systems. His hobbies—which he pursues with a passion and intelligence that would do a professional proud—include linguistics and bird-watching.

Gödel, Kurt (1906–1978): Austrian American mathematician, probably the most profound logician since Aristotle. In Vienna in 1931, Gödel proved his 2 incompleteness theorems, which established that no axiomatic mathematical system could establish all mathematical truths. Later he moved to the United States and worked at the Institute for Advanced Study at Princeton, where he counted Einstein among his few friends. Gödel continued to make startling new discoveries, including his bizarre rotating cosmology. However, he was a highly eccentric and often paranoid individual. His death was hastened by a long-term refusal to eat for fear of being poisoned.

Harrison, John (1693–1776): English inventor. In 1714, Parliament established the Longitude Prize, which authorized an award of £20,000 to anyone who could demonstrate a practical method of accurately determining the longitude of a ship at sea. In 1727, Harrison, an obscure clock maker with almost no formal education, began his decades-long effort to win the prize by developing a super-precise marine chronometer. Creating a succession of models of increasing sophistication, Harrison and his son

William eventually produced the H4, a hand-sized watch that in a trial in 1762 kept time to within 5 seconds over a voyage of 2 months. Although this was far more accurate than the prize rules demanded, Harrison still had trouble convincing the Board of Longitude (composed mostly of astronomers rather than engineers) to grant him the money. Finally, in 1765, Harrison was given £10,000, with most of the rest awarded by special act of Parliament in 1773. Harrison's quest makes an exciting story of technological discovery and personal determination.

Hawking, Stephen (b. 1942): British physicist famous both for his astounding theories and his triumph over severe physical handicap. As a brilliant young graduate student at the University of Cambridge in the early 1960s, Hawking was diagnosed with a degenerative motor neuron disease. At first daunted by this apparent death sentence, Hawking rallied and went on to do groundbreaking graduate research in general relativity. He helped to establish that the classical Einstein theory should lead to singularities where the known laws of physics break down. As his physical condition has slowly deteriorated, his intellectual achievements have became more daring. In 1973, he realized that quantum effects should cause black holes to emit radiation with a characteristic temperature. In 1983, he proposed (with James Hartle) a quantum description of the entire universe that eliminated the singularity at the start of the big bang. He continues to delve into the most profound theoretical questions about gravitation and the nature of time. Because of his popular books and his many media appearances, the wheelchair-bound theorist who speaks via computer has become a global icon. Hawking presently holds the Lucasian Chair at Cambridge, the same post previously held by Paul Dirac and Isaac Newton.

Heisenberg, Werner (1901–1976) German physicist and one of the creators of quantum mechanics. In 1924–1925, Heisenberg came to Copenhagen to work with Bohr on the new physics. There he discovered his own highly abstract version of quantum mechanics, which came to be called matrix mechanics. This was later shown to be mathematically equivalent to the wave mechanics developed by Erwin Schrödinger. Heisenberg also formulated the famous uncertainty principle, which establishes limits on our ability to know about the microscopic world. Heisenberg later made fundamental contributions to quantum field theory, nuclear physics, and elementary particle physics, including the introduction of the concept of isospin. During World War II, Heisenberg remained in Nazi Germany and directed part of the German nuclear program. This later led to considerable

strain on his relationships with physicists from other countries, and his long friendship with Niels Bohr came to an end. After the war, Heisenberg wrote extensively about the philosophical ideas embedded in quantum theory.

Helmholtz, Hermann von (1821–1894): German scientist who made basic contributions to physics, mathematics, psychology, and several other fields. It is almost impossible to give an exhaustive list of his contributions. Helmholtz began his scientific career by studying how nerves represent sense impressions, arguing that nerve impulses are abstract signs rather than direct copies of sense input. He also adapted and extended the work of Julius von Mayer and James Prescott Joule on the concept of energy. His work on fluid mechanics and electromagnetism laid the groundwork for modern mathematical field theory. Beginning in 1868, Helmholtz wrote pioneering papers on the non-Euclidean geometry of Bernhard Riemann and its possible applications to physics. He returned to thermodynamics later in life, introducing the idea of a thermodynamic potential (a measure of free energy). Although Helmholtz was sometimes wrong—as he was about the age of our solar system—he was a brilliant and imaginative scientist who pushed the boundaries of our understanding.

Joule, James Prescott (1818–1889): English physicist and one of the discoverers of the law of conservation of energy. The son and grandson of brewers, Joule took over the family business and did science as a hobby. He began by studying electricity and magnetism but later became interested in what we would now call thermodynamics. Despite the general acceptance of the caloric theory of heat, Joule built on Count Rumford Benjamin Thompson's work to establish that heat and work are 2 types of a single phenomenon, energy. Joule was able to measure the mechanical equivalent of heat, announcing his work in 1843. Almost no one paid any attention. However, over the next several years, the new point of view proved its worth, and Joule received many public honors for his contributions. Joule's work was distinguished by great ingenuity and a keen appreciation for the sources of error in an experiment. One of the basic units of energy is named in his honor.

Kamerlingh Onnes, Heike (1853–1926): Dutch physicist and pioneer of the ultracold. While professor of experimental physics at the University of Leyden, Kamerlingh Onnes built a special laboratory to create and study conditions of extreme cold, a field of study called cryogenics. With apparatus that had to confine high pressures within delicate glassware,

the occasional explosion was inevitable, but his meticulousness and determination enabled him to press on. Kamerlingh Onnes was the first to liquefy helium (1908) and the first to observe the phenomenon of superconductivity (1911). By the 1920s, his lab had produced a temperature less than one degree above absolute zero, the coldest temperature yet achieved on Earth. Contemporary press stories called him "the gentleman of absolute zero."

Laplace, Pierre-Simon (1749–1827): French mathematician and physicist notable for fundamental work in Newtonian physics. Laplace was a protégé of the mathematician Jean Le Rond d'Alembert, but he soon began to eclipse his sponsor. His increasing fame and respect, however, did not mean that he always got along well with his fellow scholars. Laplace's tendency to adjust his political opinions according to the current climate kept him relatively safe in the turbulent years during and after the French Revolution, but it cost him many friends. Laplace advanced differential equations, probability theory, and celestial mechanics. He proved that the orbits of the planets were stable over long periods of time, thus settling a question that Newton had been unable to solve. Laplace was a thoroughgoing rationalist; when asked by Napoleon why he did not mention God in his work on celestial mechanics, he famously answered, "I had no need of that hypothesis."

Lee, Tsung-Dao (b. 1926): Chinese American physicist who, with Chen Ning Yang, discovered parity asymmetry in beta decay. Like Yang, he was born in China and then came to the University of Chicago after World War II, where Lee worked with Enrico Fermi. Lee has been a professor at Columbia University for more than 50 years and has published more than 300 scientific papers on subjects ranging from statistical physics to nuclear interactions to astrophysics and fluid mechanics. J. Robert Oppenheimer once praised his work for its "remarkable freshness, versatility, and style."

Lorenz, Edward (1917–2008): American atmospheric scientist whose studies of dynamical systems inaugurated chaos theory. After work as a weather forecaster in World War II, Lorenz earned a doctorate in meteorology from MIT and then spent his career on the faculty there. In 1961, he was investigating the use of computers to calculate a simplified model of a weather system. The strange behavior of the model led to the startling realization that even a fairly simple deterministic system might not actually be predictable. His paper, published 2 years later, launched

a revolution in science. With the computer as their microscope, Lorenz and his colleagues were at last able to follow the hints and clues in Henri Poincaré's work on nonlinear dynamics, finding powerful insights into the complex behavior of physical, chemical, and even biological systems.

Mach, Ernst (1838–1916): Austrian physicist famed both for his scientific research and his penetrating work on the philosophy of science. Like Helmholtz, Mach did some of his early work on experimental psychology, studying perception, and in fact Mach turned down a job as chair of surgery at the University of Salzburg to pursue mathematics and physics. Mach's study of shock waves in supersonic flows was fundamental in high-speed aerodynamics; the Mach number, expressing the ratio of speed to the speed of sound, is named for him. He made a careful analysis and critique of the conceptual basis for Newtonian mechanics. Mach's philosophy was a variety of logical positivism, which led him to deny the reality of theoretical constructs. Thus he refused to believe in the real existence of atoms until the very end of his life. His skeptical attitude and unorthodox thinking were an inspiration to many physicists, particularly Albert Einstein.

Maxwell, James Clerk (1831–1879): Scottish mathematician and physicist who made fundamental contributions to mechanics and electromagnetism. He applied Newtonian mechanics to the behavior of huge numbers of colliding molecules, deriving the statistical distribution of molecular speeds in a gas. He also derived many useful mathematical relations in the science of thermodynamics. His famous thought experiment, called Maxwell's demon, emphasized the probabilistic nature of the second law of thermodynamics. By collecting and analyzing the known laws of electromagnetism, Maxwell realized that the system was mathematically incomplete. When he supplied the missing pieces, he discovered that electromagnetic disturbances travel through space in the form of polarized waves with a speed equal to that of light. His conclusion that light is an electromagnetic wave unified optics and electromagnetism and also indicated the possible existence of other related waves. The later discovery by Heinrich Hertz of radio waves vindicated Maxwell's theory. Maxwell himself was a religious man, a guitar player, and the author of several amusing songs about physics and its study.

Mayer, Julius von (1814–1878): German physician and scientist and one of the discoverers of the law of conservation of energy. Interestingly, Mayer reached this great principle via a physiological approach. As a ship's

doctor on a voyage to the East Indies, Mayer noted that the blood of the crew members was more red in a warm climate. He concluded that the warm temperature led to a reduced demand for oxygen, and this, in turn, led him to conjecture that the oxidation of food was the source of bodily heat. After his return home, he pursued these ideas and published his work, including a quantitative relation between heat and mechanical work, in 1842. However, because he was a relatively unknown scholar outside of the scientific establishment, his discovery received little notice at the time. After the death of 2 of his children, he attempted suicide and then spent a decade in a mental asylum. When he emerged in 1860, his reputation as a scientist had grown throughout Europe. He was awarded the Copley Medal from the Royal Society in 1871.

Minkowski, Hermann (1864–1909): Polish German mathematician who introduced the concept of space-time. Minkowski was a pure mathematician with interests in algebra, geometry, and number theory. After doctoral work at Königsburg, he held various professorships in Central Europe. During his time in Zurich, he was one of Einstein’s mathematics professors. In 1902, a position was created for him at the University of Göttingen by the great David Hilbert, and Minkowski taught there for the rest of his life. Hilbert got Minkowski interested in problems of mathematical physics, and it was at Göttingen that Minkowski realized that Einstein’s relativity could be recast as a theory of space-time geometry. Einstein, who at first held that mathematical elegance should be secondary to physical intuition, eventually came to adopt his old teacher’s idea wholeheartedly. Minkowski died quite suddenly at the age of 44 from a ruptured appendix.

Newton, Isaac (1642–1727): English physicist and mathematician and without doubt the greatest scientific mind of his age. In his book *Mathematical Principles of Natural Philosophy* (1687), Newton established the science of mechanics based on universal laws of motion and gravitation. This work explained motions ranging from projectiles on Earth to the orbits of the planets, together with a host of other phenomena. Newton invented calculus, which he called the method of fluxions, to deal with his new system of mechanics. Newtonian mechanics was the basis for physics for more than 2 centuries. Newton also made tremendous contributions to optics, including the invention of the reflecting telescope and the discovery that white light is a mixture of all colors. In addition to his scientific pursuits, Newton commented on scripture, wrote about theology, and studied alchemy. Newton was a powerful and influential figure in the

English science of his day and served as president of the Royal Society of London from 1701 to his death.

Nishijima, Kazuhiko (1926–2009): Japanese physicist who, with Murray Gell-Mann, showed how the idea of strangeness explained the behavior of elementary particles. In the 1950s, new types of particles were being discovered every few months, and it was a major challenge to make sense of their properties. Nishijima and Gell-Mann independently determined that some order could be brought to the confusion by identifying a new, approximately conserved quantity. (The term "strangeness" was coined by Gell-Mann; Nishijima called it eta charge.) The Gell-Mann–Nishijima formula they discovered relates electric charge, isospin, and strangeness and became an important clue to the existence of quarks. Nishijima spent his career at universities in Japan, Europe, and the United States; starting in 1996, he served as a distinguished professor at the University of Tokyo.

Noether, Emmy (1882–1935): German mathematician, probably the greatest female mathematician in history. The daughter of a mathematics professor at the University of Erlangen, Noether originally intended to become a language teacher. Her tremendous talent and passion for mathematics, however, changed her path. Even after earning her doctorate in 1907, she was not permitted as a woman to gain an academic post in the German university system. She stayed in Erlangen assisting her father, but her brilliant work caused her reputation to grow. In 1915, she was invited by the great David Hilbert to join the mathematics faculty at Göttingen. Once there, Noether was not allowed to teach in her own name for several years; Hilbert got around this restriction by having her "assist" in courses officially assigned to him. Noether's many contributions included the famous theorem of mathematical physics bearing her name and the creation of the entire subfield of algebra now called Noetherian rings. Because of her Jewish descent, Noether was forced to leave Göttingen when the Nazis came to power in 1933. She ended up at Bryn Mawr College in the United States, where she taught until her death.

Pauli, Wolfgang (1900–1958): Austrian physicist, later an American citizen and a resident of Switzerland, famous for his brilliant discoveries in theoretical physics and his sharp critique of shaky reasoning. Pauli developed his exclusion principle in 1924 to explain the structure of many-electron atoms. He was the first to use quantum mechanics to explain atomic spectra, and he contributed a great deal to the theory of particle spin.

In 1929, he proposed that the mysteries of beta decay (one of the main types of radioactivity) could be explained by the existence of an almost-invisible ghost particle, later called the neutrino by Enrico Fermi. When the neutrino was finally discovered almost 30 years later, the discoverers sent a telegram congratulating Pauli. His reply: "Thanks for the message. Everything comes to him who knows how to wait." Pauli was well known for his ready and caustic wit, and anecdotes about his various remarks are favorites among physicists. (Of one paper he said, "This isn't right. This isn't even wrong.")

Planck, Max (1858–1947): German physicist and the originator of the quantum hypothesis. For most of his career, Planck was a professor at the University of Berlin. In the last years of the 19th century, he turned his attention to the problem of understanding the electromagnetic radiation emitted by hot bodies of all sorts. Since all blackbodies, regardless of composition, emit radiation with the same characteristics, Planck recognized this as a problem of fundamental importance. His early work met with only partial success. Finally, in 1900, he adopted the quantum hypothesis as, in his words, "an act of despair." Though it involved a radical departure from previous ideas about energy, Planck's new theory accounted for blackbody radiation with great exactness. Planck observed the subsequent development of quantum theory with great interest. With a sad wisdom, he wrote, "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

Poincaré, Henri (1854–1912): French mathematician who contributed significantly to almost every branch of mathematics, from topology to complex functions. Poincaré was probably the last mathematician with such a wide range of expertise. He also made significant contributions to physics. His work on the 3-body problem, undertaken to compete for a prize offered by the king of Sweden, laid the groundwork for the later science of chaos theory. (Poincaré won the prize.) His work on the symmetries of Maxwell's equations led him to most of the ideas of special relativity, independent of Albert Einstein's work. Of mathematics, Poincaré wrote, "It is by logic that we prove, it is by intuition that we invent." His own elegant work, leaping from insight to insight, was very much a marriage of these 2 aspects. At his funeral, one of the speakers described him thus: "mathematician, geometer, philosopher, and man of letters, who was a kind of poet of the infinite, a kind of bard of science."

Rosen, Nathan (1909–1995): American Israeli physicist. Born in Brooklyn, Rosen was educated at MIT and from 1934 to 1936 was Albert Einstein's assistant at Princeton. The pair of them explored at least 2 significant ideas: quantum entanglement (in a famous paper with Boris Podolsky) and the possibly of wormholes connecting remote regions of space. Rosen also helped to illuminate the quantum structure of the hydrogen molecule. He moved to Israel in 1953 and joined the faculty of Technion, helping to establish it as a leading institution of science and technology.

Sagan, Carl (1934–1996): American astronomer, visionary, and popularizer of science. Sagan was one of the world's leading planetary scientists. He was the first to realize that the greenhouse effect would make the surface of Venus extremely hot, and many of his other inferences and speculations about conditions on planets and moons have also been confirmed. He was heavily involved in NASA's robotic exploration of the planets. Sagan believed that our galaxy is most likely teeming with intelligent life and that the search for this life (called SETI) was one of the greatest scientific quests in human history. His popular books and television appearances inspired a generation of space scientists; his novel *Contact* inspired serious research on wormholes in space-time. Sagan was one of the most recognizable scientists in the world and a tireless advocate for environmental protection and nuclear arms control.

Schrödinger, Erwin (1887–1961): Austrian physicist and one of the developers of quantum mechanics. Schrödinger's version, called wave mechanics, was at first seen as a competitor to Heisenberg's wave mechanics before Paul Dirac showed them to be mathematically equivalent. Like so many of the physicists of Germany, Italy, and Austria, Schrödinger was obliged to leave in the early 1930s as the Nazis took power. He settled in Dublin, founding the Institute for Advanced Study at the university there and writing an influential book, *What Is Life?*, about the physical nature of biological systems. This book inspired physicist Francis Crick to switch fields and become one of the discoverers of the structure of DNA. Schrödinger returned to Vienna for the last few years of his life.

Schwarzschild, Karl (1873–1916): German astrophysicist who discovered the mathematical description of a black hole. Schwarzschild was an astronomer, working in observatories and universities in Munich, Göttingen, and Potsdam. He pioneered the use of photometry to study variable stars. He also speculated that the geometry of space might be non-Euclidean and

in fact tried to estimate its curvature observationally. When Albert Einstein's general theory of relativity was announced, Schwarzschild was a soldier on the Russian front in World War I. He quickly found an exact mathematical solution to Einstein's equations, one that was later recognized as the description of a black hole. Einstein saw to the publication of this work, but Schwarzschild himself contracted an illness in the trenches and died the same year. The German Astronomical Society's Schwarzschild Medal was named for him, and the award's first recipient was astronomer Martin Schwarzschild, his son.

Shannon, Claude (1916–2001): American mathematician and engineer, founder of information theory. Shannon's many discoveries have been of incalculable importance in creating the information age. His MIT master's thesis in 1937 laid the abstract groundwork for the digital computer. After World War II, he developed the mathematical theory of communication and soon applied it to everything from signal processing to human language to cryptography. He was a prolific inventor and game player, applying his genius to robotics, gambling, the stock market, and computer chess. One famous example of his playful intellect was a mathematical analysis showing that the redundancy of English makes crossword puzzles possible. Shannon did much of his work at Bell Labs, later joining the faculty at MIT.

Smoluchowski, Marian (1872–1917): Polish physicist and mathematician who made numerous discoveries in statistical mechanics. Smoluchowski was a contemporary of Albert Einstein, and they worked on many of the same problems in statistical physics and thermodynamics, such as critical opalescence. Smoluchowski worked at universities throughout Europe before settling down in his native Poland. He was honored not only as a physicist but also as a mountaineer.

Stevin, Simon (1548–1620): Dutch physicist and mathematician also known as Stevinus. Stevin was a near contemporary to Galileo and one of the founders of the science of mechanics. Remarkably little is known of his life. He served in various government posts, including director of public works and quartermaster-general of the army. He wrote several treatises on theoretical and practical mathematics, and he introduced the use of decimal fractions to Europe. His discoveries about force and motion included his observation that bodies of different size fall with the same acceleration—something later found independently by (and usually attributed to) Galileo. He also wrote books about music, political theory, and the design of fortifications.

Thompson, Rumford Benjamin (1753–1814): American expatriate physicist and one of the grandfathers of thermodynamics. Thompson was born and educated in New England but was forced to leave due to his Loyalist sympathies during the American Revolution. He moved to England and then on to Bavaria, where he worked for the Prince-Elector. For his services, he was made a count of the Holy Roman Empire. While supervising the boring of cannon in Bavaria, he made his great discovery that heat and work are equivalent, laying the groundwork for the law of conservation of energy. Later he moved back to England, founding the Royal Institution; then he moved to France (marrying the widow of the great chemist Antoine Lavoisier). He is buried in Paris.

Thomson, Lord Kelvin William (1824–1907): Scottish physicist who introduced the concept of absolute zero. Thomson was something of a prodigy, studying in Glasgow, Cambridge, and Paris before being named professor of natural philosophy at Glasgow University at the age of 22. He served in that post for more than 50 years. His initial reluctance to accept the thermodynamical ideas of James Prescott Joule and Rudolf Clausius did not prevent him from inventing the absolute scale of temperature that was later named in his honor. His work on mathematical analogies between heat, electricity, and magnetism later inspired James Clerk Maxwell and others. He was also a skilled experimenter, discovering several new phenomena and designing new electrical instruments. Thomson was knighted and later made Baron Kelvin of Largs for his work on the transatlantic telegraph cable. He gained great fame and prestige, which did not prevent him from being fairly often mistaken on matters from X-rays to practical aviation. Yet his students and colleagues remembered him for his kindliness and his infectious enthusiasm for physics.

Thorne, Kip (b. 1940): American physicist who has studied the astrophysical implications of Einstein's general relativity. In a long career at Caltech, Thorne has worked out many of the properties of black holes and their interactions with surrounding matter. He also studied the production and detection of gravitational waves, which are moving disturbances in the geometry of space-time. His work on wormholes inspired deep speculations about the nature of space-time and the possibility of time travel, but he also helped to identify physical effects that may prevent the formation of causal loops. In 2009, Thorne retired from Caltech to work on writing projects, including a proposed movie with Steven Spielberg.

Wells, Herbert George (1866–1946): English author and one of the most notable public intellectuals of his time. After failing as a draper, a chemist's assistant, and a teacher, Wells came to the public attention with a series of exciting and thought-provoking science fiction tales, including *The Time Machine*, *The War of the Worlds*, and *The First Men in the Moon*. These became some of the prototypes of the young genre. But Wells was interested in much more, and he went on to write conventional novels, popular science, essays, history, social criticism, and even a charming little book on wargaming. His work *The Outline of History* was a very influential study of the development of human civilization and remains in print today. Wells was a Fabian socialist and a religous free thinker. His predictions of future social and technological developments included the suburb, the spaceship, the armored tank, and the atomic bomb.

Wu, Chien-Shiung (1912–1997): Chinese American physicist who experimentally confirmed that nature distinguishes between left and right (parity asymmetry). In 1936, Wu came to the United States from China to study physics with E. O. Lawrence at Berkeley. After receiving her Ph.D., she went on to participate in the Manhattan Project during World War II. Her beta decay experiment confirmed the theoretical ideas of Chen Ning Yang and Tsung-Dao Lee and became one of the most famous scientific experiments in 20th-century physics. Her research led her to literally write the book on beta decay. She served as president of the American Physical Society (the first woman to do so) and has received many honors, including the prestigious Wolf Prize. She did not, however, share the Nobel Prize with Yang and Lee.

Yang, Chen Ning (b. 1922): Chinese American physicist who, with Tsung-Dao Lee, discovered parity asymmetry in beta decay. Yang grew up in China, moving to the United States after World War II to study physics at the University of Chicago. He obtained his doctorate there under the supervision of Edward Teller. Yang's collaboration with Lee began while they were at the Institute for Advanced Study at Princeton. With Robert Mills, he also developed the basic theory of gauge fields that forms the basis for the modern standard model of particle physics. Yang has long divided his time between academic institutions the United States and China. His official Nobel biography describes him as a "hard worker" who allows himself "very little leisure time."

Bibliography

Aczel, Amir D. *Entanglement: The Greatest Mystery in Physics*. New York: Plume, 2001. Exactly as you would expect from the author and title, this is a well-written, interesting, popular book about quantum physics, focusing on quantum entanglement and its implications.

Asimov, Isaac. *The Left Hand of the Electron*. New York: Doubleday, 1972. Science fiction writer and biochemist Isaac Asimov wrote literally hundreds of books on almost every topic imaginable. Some of his most enjoyable writing is found in his monthly essays on science for *The Magazine of Fantasy and Science Fiction*, which he wrote for more than 3 decades. This book is a collection (the ninth) of these articles. The first 5 chapters give a beautifully clear explanation of the C, P, and T symmetries of particle physics and also the role of symmetry and asymmetry in the structure of molecules.

Carnot, Sadi. *Reflections on the Motive Power of Fire*. New York: Dover, 1960. Carnot's little book, written in 1824, is surprisingly accessible to the modern reader, and his brilliant insights about heat and work continue to impress.

Clarke, Arthur C. *Profiles of the Future: An Inquiry into the Limits of the Possible*. New York: Harper and Row, 1962. Clarke, a noted writer of both science fiction and popular science, makes a serious effort here to envision scientific and technological developments for the next century. His introductory chapters on the hazards of prediction are worth the price of the book. Clarke did publish a new, updated edition of the book in 2000, and it is the newer version that contains all 3 of Clarke's laws. However, the original is still excellent and is much easier to find.

Davis, Philip J., and David Park. *No Way: The Nature of the Impossible*. New York: W. H. Freeman, 1987. This wide-ranging and thought-provoking book contains essays by many authors about what the impossible means, in subjects from mathematics to economics.

Falletta, Nicholas. *The Paradoxicon*. Garden City: Doubleday, 1983. This delightful book is a collection of paradoxes ranging from the ancient Greeks to modern set theory. Think of this as a field guide to absolute impossibility.

Feynman, Richard Phillips. *The Character of Physical Law*. Cambridge: MIT Press, 1965. Richard Feynman was both a brilliant physicist and a brilliant explainer of physics. His 1964 Messenger Lectures at Cornell University is perhaps the best description of the essential nature of physics. This is one of my favorite books. The lectures were filmed by the BBC, but the video or audio versions are much harder to find.

Ford, Kenneth. W. *The Quantum World: Quantum Physics for Everyone*. Cambridge, MA: Harvard University Press, 2004. Ford, who used to be the director of the American Insitute of Physics, has written an outstanding popular account of quantum theory and its impact on physics.

Gamow, G. *Thirty Years That Shook Physics: The Story of Quantum Theory*. Mineola, NY: Dover, 1966. A great account of the historical development of quantum physics from 1900 to 1930, illustrated with the author's inimitable cartoons. Gamow was involved in this story and knew all the principals very well, so this book is also filled with character sketches and funny stories. The last chapter is the script of the spoof of *Faust* that we mentioned in Lecture Four, first performed in 1932 by Bohr's students at his institute in Copenhagen.

Gardner, Martin. *Time Travel and Other Mathematical Bewilderments*. New York: W. H. Freeman, 1988. Gardner's regular column in *Scientific American* on mathematical games, which ran for nearly 25 years, was always an intellectual treat. This book is a collection of some of these columns. The first essay, from which the book draws its name, is an elegant summary of the literary and scientific aspects of time travel.

Gleick, James. *Chaos: Making a New Science*. New York: Viking, 1987. Gleick's outstanding book, which was an international best seller, is still the indispensable popular account of the history and development of chaos theory.

Gott, J. Richard. *Time Travel in Einstein's Universe: The Physical Possibilities of Travel through Time*. New York: Houghton Mifflin, 2001. A Princeton astrophysicist explains Gödel's rotating cosmos and other possibilities for time travel within the framework of Einstein's general relativity.

Grant, John. *Discarded Science: Ideas That Seemed Good at the Time*. Wisley: Facts, Figures & Fun, 2006. This book is a knowledgeable and fun sampling of all sorts of scientific and pseudoscientific theories that have at one time or another gained serious followings. Our interest in this charming

book lies mostly in chapter 5, which contains nice discussions of both the caloric theory of heat and perpetual motion machines.

Kaku, Michio. *Physics of the Impossible: A Scientific Exploration into the World of Phases, Force Fields, Teleportation, and Time Travel*. New York: Doubleday, 2008. Kaku, himself a well-regarded theoretical physicist, is also one of the most engaging popularizers of physics writing today. This book addresses many of the same topics we cover in this course, though with a different point of view.

Leff, Harvey S. and Andrew F. Rex, eds. *Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing*. Bristol, UK: Institute of Physics, 2003. In 1992, Leff and Rex gathered the fundamental scientific papers on Maxwell's demon into a single handy volume, an instant classic. Unfortunately, at about the same time, a new and deeper understanding of the demon (including quantum mechanical aspects) was being worked out, so in a few years a new, up-to-date edition was needed. This is it. Some of the papers here are technical, but the introductory essay and the wide historical scope of the book make it an indispensable resource for the serious student.

McEvoy, J. P. and Oscar Zarate. *Introducing Quantum Theory: A Graphing Guie to Science's Most Puzzling Discovery*. Cambridge: Icon Books, 2007. This looks like a pocket-sized cartoon book. In fact, it is a superb and sometimes hilarious discussion of the development of quantum theory.

Polkinghorne, J. *The Quantum World*. New York: Longman, 1984. A very fine, brief introduction to the ideas of quantum physics, including entanglement. Although the text is not highly technical, the appendix fills in the math for those who are interested.

Postgate, John. *The Outer Reaches of Life*. Cambridge: Cambridge University Press, 1994. Extremophiles—microbes that live and thrive in the most extreme sorts of conditions—are the subject of this wonderful book. The surprising story of high-temperature life is told in chapter 2.

Siegfried, Tom. *The Bit and the Pendulum: From Quantum Computing to M Theory—The New Physics of Information*. New York: John Wiley & Sons, 2000. This is the first of several books by writer Tom Siegfried, who later became editor-in-chief of *Science News*. The book describes how scientists have come to realize the central role of information in fundamental physics, from thermodynamics to quantum physics and beyond. (I have always

had high regard for Siegfried as one of the best science journalists in the business, one who consistently gets it right even in quite difficult subjects.)

Sobel, Dava. *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time.* New York: Walker, 1995. Sobel's wonderfully readable account of the problem of the Longitude Prize and John Harrison's amazing clocks became a best seller when published and was soon adapted into a television film. Sobel also tells the story of Rupert Gould, who found, studied, and restored Harrison's clocks in the early 20th century. Some have criticized the book, saying it overemphasizes the conflict between Harrison and the astronomers on the Board of Longitude, but it remains a superb and informative read.

Taylor, Edwin F. and John A. Wheeler. *Spacetime Physics*. New York: W. H. Freeman, 1992. An introduction, both accessible and sophisticated, to relativity and the space-time view of physics. With a few well-chosen mathematical tools, Taylor and Wheeler are able to lead the reader through some pretty advanced ideas. The problems are vivid and imaginative (and full solutions are given); the diagrams are a delight. Curved space-time and gravitation are not neglected, though this section has a more qualitative emphasis.

Thorne, Kip S. *Black Holes and Time Warps: Einstein's Outrageous Legacy*. New York: W. W. Norton, 1994. Thorne, a distinguished physicist from Caltech, has written an accessible yet serious introduction to the ideas of curved space-time, black holes, Hawking radiation, and so on. The last part of the book discusses the possibility and implications of wormholes in space-time—a subject that Thorne himself pioneered.

Van Ness, H. C. *Understanding Thermodynamics*. New York: Dover, 1969. A slender conceptual introduction to the basics of thermodynamics, originally given as a series of lectures to engineering students at Rensselaer Polytechnic Institute. It is hard to beat this as a general (and relatively gentle) orientation in the broad subject of energy and its transformations.

Wheeler, John A. *A Journey into Gravity and Spacetime*. New York: Scientific American Library, 1990. One of the greatest experts on Einstein's general theory of relativity gives a superb and slightly quirky account of curved space-time. Wheeler was famous for his quirky approach, his dramatic turn of phrase, and his outstanding visualizations of recondite mathematical ideas. Here is the book in a nutshell: "Space-time tells matter how to move; matter tells space-time how to curve."

Online Resources

"Absolute Zero." *NOVA*. WBGH, 2008. This 2-part episode of the award-winning science series on PBS gives vivid insights into the technology and science of extreme cold. Of special interest is the surprisingly exciting story of the late 19th-century race between scientists in different countries to liquefy every known gas and achieve the coldest possible temperature. The entire documentary, together with many supporting materials, can be found online at http://www.pbs.org/wgbh/nova/zero/.

Euclid's Elements. http://aleph0.clarku.edu/~djoyce/java/elements/toc.html. At this website, maintained by David E. Joyce at Clark University, Euclid's famous treatise on geometry and numbers has been recreated in 21st-century form. All of the original definitions, axioms, propositions, and proofs are here (in English), together with background material, commentary, explanations, and hypertext links that trace the logical relationships.

MacTutor Math History Archives—Biographies Index. http://www-history.mcs.st-and.ac.uk/history/BiogIndex.html. Maintained at the University of St. Andrews in Scotland, this website includes a database of detailed biographies of literally thousands of mathematicians, together with a great many physicists and astronomers. The database can be accessed by name, country, or century. This is probably the best single online resource for information about the people who created modern mathematical science.

The Museum of Unworkable Devices. http://www.lhup.edu/~dsimanek/museum/unwork.htm. This website, maintained by Donald E. Simanek, is full of excellent illustrations, fascinating history, and sometimes hilarious ideas. It is the go-to place on the internet for information on perpetual motion machines. (One commenter describes it as an "eclectic debunkorie.") The museum and its galleries richly reward repeated visits.

Science Fiction Books and Films

Back to the Future. This series of 3 movies (released in 1985, 1989, and 1990) starred Michael J. Fox and Christopher Lloyd. Using a time machine installed in a DeLorean sports car, the hero goes backward and forward in time, creating (and attempting to untangle) various time paradoxes. The meticulous work of director Robert Zemeckis and screenwriter Bob Gale makes it fun to watch for even the smallest details.

Contact. The 1985 novel by astronomer Carl Sagan was adapted 12 years later into a film directed by Robert Zemeckis. The novel is a thoughtful, multifaceted story about the discovery of a radio signal from extraterrestrials and the resulting consequences for humanity. The book has the unusual distinction of having inspired a serious line of theoretical physics research (by Kip Thorne and others) into the physics of space-time wormholes. The film adaptation, starring Jodie Foster and Matthew McConaughey, is excellent.

Doppelgänger (a.k.a. *Journey to the Far Side of the Sun*). Written and produced by British filmmakers Gerry and Sylvia Anderson, this 1969 film recounts a space mission to a strange planet orbiting exactly opposite Earth. The planet turns out to be a mirror image of Earth itself. The Andersons made numerous other science fiction television shows and films; this is probably the best of the lot.

Forbidden Planet. This big-budget 1956 film from MGM marked a breakthrough, drawing top stars (Walter Pidgeon, Anne Francis, and Leslie Nielsen) to a story about interstellar travel and a mysterious alien planet. (The plot and characters seem drawn right from the *Star Trek* television series, which was in fact made a decade later.) With a literate script and special effects by Disney, this set a standard that few contemporary science fiction films were able to match.

The Incredible Shrinking Man. Richard Matheson wrote the novel in 1956, then helped adapt it into a film the following year. For unknown reasons, a man begins to shrink in size, a little more each day. Growing estrangement from normal human beings, especially his wife, provides drama; harrowing battles with a house cat and a basement spider provide thrills. In the end, the hero accepts his fate and faces the unknown microscopic realm. The film is thus a tragedy.

Them! Released in 1954, this is one of the original—and best—of the 1950s science fiction monster films. Though the special effects seem primitive by today's standards, an exciting premise (giant ants!) and an intelligent script make this worth watching. James Arness plays the hero, an FBI agent called to investigate mysterious events in the New Mexico desert. Just a couple of years earlier, he had played the monster in Howard Hawks's *The Thing*.

The Time Machine. H. G. Wells's 1895 novel spawned countless successors and several film and television productions. In Lecture Four we mention the 1960 film version starring Rod Taylor. It was directed by George Pal, who

also produced several films of other classic science fiction stories, including *The War of the Worlds*, *Destination Moon*, and *When Worlds Collide*.

2001: A Space Odyssey. This is both a novel by Arthur C. Clarke published in 1968 and a film directed by Stanley Kubrick released in the same year. *2001* became a landmark in the history of science fiction films, both because of its dazzling visual effects and its intriguing—and sometimes mysterious—themes.